



Department of Research Evaluation

LTCI*

LABORATOIRE TRAITEMENT ET
COMMUNICATION DE L'INFORMATION

SELF-ASSESSMENT DOCUMENT

2018 - 2023

—
GROUP E
2024-2025 EVALUATION CAMPAIGN

Haut Conseil de l'évaluation de la recherche et de l'enseignement supérieur

Contents

I	GENERAL INFORMATION & PORTFOLIO INTRODUCTION	10
1	General information	11
1.1	Unit identification	11
1.2	Presentation of the LTCI	11
1.2.1	History, location of the unit	11
1.2.2	Structure of the unit	12
1.2.3	Platforms, equipment, and shared services	14
1.2.4	Size and composition of the teams	16
1.2.5	Scientific orientations of the unit and its teams	16
1.3	Scientific subjects and their implications	18
1.3.1	Data Science & Artificial Intelligence	18
1.3.2	Visual and Audio Computing, Interaction	19
1.3.3	Digital Trust	19
1.3.4	Embedded Systems	20
1.3.5	Communication Systems & Networks	21
1.3.6	Mathematics & Applications	21
1.4	Resources	22
1.4.1	PhD, postdocs, research engineers and interns	22
1.4.2	Financial resources	22
1.5	Activity profile	24
1.6	Research environment	24
1.7	Consideration of the recommendations of the previous report	26
1.7.1	Unit level recommendations	26
1.7.2	Teams level recommendations	28
2	Portfolio introduction	43
2.1	Communications and Electronic	43
2.1.1	C2S Team	43
2.1.2	ComNum Team	44
2.1.3	GTO Team	44
2.1.4	LabSoC Team	45
2.1.5	RFM ² Team	45
2.1.6	SSH Team	46
2.2	Computer Science and Networks	47
2.2.1	ACES Team	47
2.2.2	C2 Team	47
2.2.3	DIG Team	48
2.2.4	DIVA Team	48
2.2.5	QURIOSITY Team	49
2.2.6	RMS Team	49
2.3	Image, Data and Signal	50
2.3.1	IMAGES Team	50

2.3.2	MM Team	51
2.3.3	S ² A Team	51
II TEAMS SELF-ASSESSMENT		53
3	Self-assessment of C2S team	54
3.1	Profile, Resources and Organization	54
3.1.1	Scientific objectives	54
3.1.2	Resources	54
3.1.3	Human resources management, safety, environment, ethical protocols, data and scientific heritage protection	55
3.1.4	Synthetic self-assessment	55
3.2	Attractiveness	56
3.2.1	Scientific reputation and contributions	56
3.2.2	Staff hosting policy	56
3.2.3	Success in competitive calls for projects	57
3.3	Scientific Production	57
3.3.1	Qualitative analysis	57
3.3.2	Potential and dissemination strategy	59
3.3.3	Scientific integrity, ethics and open science	60
3.4	Contribution of Research Activities to Society	60
3.4.1	Socioeconomic partnerships and interactions	60
3.4.2	Research valorization and transfer	60
3.4.3	Science popularization	60
4	Self-assessment of ComNum team	61
4.1	Profile, Resources and Organization	61
4.1.1	Scientific objectives	61
4.1.2	Resources	61
4.1.3	Human resources management, safety, environment, ethical protocols, data and scientific heritage protection	62
4.1.4	Synthetic self-assessment	63
4.2	Attractiveness	63
4.2.1	Scientific reputation and contributions	63
4.2.2	Staff hosting policy	65
4.2.3	Success in competitive calls for projects	65
4.2.4	Equipment quality and technological skills	65
4.2.5	Synthetic self-assessment	66
4.3	Scientific Production	66
4.3.1	Qualitative analysis	66
4.3.2	Potential and dissemination strategy	67
4.3.3	Scientific integrity, ethics and open science	67
4.3.4	Synthetic self-assessment	67
4.4	Contribution of Research Activities to Society	67
4.4.1	Socioeconomic partnerships and interactions	67
4.4.2	Research valorization and transfer	68
4.4.3	Science popularization	68
4.4.4	Synthetic self-assessment	69

5	Self-assessment of GTO team	70
5.1	Profile, Resources and Organization	70
5.1.1	Scientific objectives	70
5.1.2	Resources	71
5.1.3	Human resources management, safety, environment, ethical protocols, data and scientific heritage protection	71
5.1.4	Synthetic self-assessment	71
5.2	Attractiveness	72
5.2.1	Scientific reputation and contributions	72
5.2.2	Staff hosting policy	73
5.2.3	Success in competitive calls for projects	73
5.2.4	Equipment quality and technological skills	73
5.2.5	Synthetic self-assessment	74
5.3	Scientific Production	74
5.3.1	Qualitative analysis	74
5.3.2	Potential and dissemination strategy	78
5.3.3	Scientific integrity, ethics and open science	78
5.3.4	Scientific Highlights	78
5.3.5	Synthetic self-assessment	81
5.4	Contribution of Research Activities to Society	81
5.4.1	Socioeconomic partnerships and interactions	81
5.4.2	Research valorization and transfer	81
5.4.3	Science popularization	81
5.4.4	Synthetic self-assessment	82
6	Self-assessment of LabSoC team	83
6.1	Profile, Resources and Organization	83
6.1.1	Scientific objectives	83
6.1.2	Resources	84
6.1.3	Human resources management, safety, environment, ethical protocols, data and scientific heritage protection	84
6.1.4	Synthetic self-assessment	85
6.2	Attractiveness	85
6.2.1	Scientific reputation and contributions	85
6.2.2	Staff hosting policy	85
6.2.3	Success in competitive calls for projects	85
6.2.4	Equipment quality and technological skills	86
6.2.5	Synthetic self-assessment	86
6.3	Scientific Production	86
6.3.1	Qualitative analysis	86
6.3.2	Potential and dissemination strategy	88
6.3.3	Scientific integrity, ethics and open science	88
6.3.4	Synthetic self-assessment	88
6.4	Contribution of Research Activities to Society	88
6.4.1	Socioeconomic partnerships and interactions	88
6.4.2	Research valorization and transfer	89
6.4.3	Science popularization	89
6.4.4	Synthetic self-assessment	89

7	Self-assessment of RFM² team	90
7.1	Profile, Resources and Organization	90
7.1.1	Scientific objectives	90
7.1.2	Resources	91
7.1.3	Human resources management, safety, environment, ethical protocols, data and scientific heritage protection	91
7.1.4	Synthetic self-assessment	91
7.2	Attractiveness	92
7.2.1	Scientific reputation and contributions	92
7.2.2	Staff hosting policy	93
7.2.3	Success in competitive calls for projects	93
7.2.4	Equipment quality and technological skills	94
7.2.5	Synthetic self-assessment	94
7.3	Scientific Production	94
7.3.1	Qualitative analysis	94
7.3.2	Potential and dissemination strategy	96
7.3.3	Scientific integrity, ethics and open science	96
7.3.4	Synthetic self-assessment	96
7.4	Contribution of Research Activities to Society	97
7.4.1	Socioeconomic partnerships and interactions	97
7.4.2	Research valorization and transfer	97
7.4.3	Science popularization	97
7.4.4	Synthetic self-assessment	97
8	Self-assessment of SSH team	98
8.1	Profile, Resources and Organization	98
8.1.1	Scientific objectives	98
8.1.2	Resources	98
8.1.3	Human resources management, safety, environment, ethical protocols, data and scientific heritage protection	99
8.1.4	Synthetic self-assessment	100
8.2	Attractiveness	100
8.2.1	Scientific reputation and contributions	100
8.2.2	Staff hosting policy	101
8.2.3	Success in competitive calls for projects	101
8.2.4	Equipment quality and technological skills	102
8.2.5	Synthetic self-assessment	102
8.3	Scientific Production	102
8.3.1	Qualitative analysis	102
8.3.2	Potential and dissemination strategy	106
8.3.3	Scientific integrity, ethics and open science	107
8.3.4	Synthetic self-assessment	107
8.4	Contribution of Research Activities to Society	107
8.4.1	Socioeconomic partnerships and interactions	107
8.4.2	Research valorization and transfer	107
8.4.3	Science popularization	107
8.4.4	Synthetic self-assessment	107
9	Self-assessment of ACES team	108
9.1	Profile, Resources and Organization	108
9.1.1	Scientific objectives	108
9.1.2	Resources	108
9.1.3	Human resources management, safety, environment, ethical protocols, data and scientific heritage protection	110

9.1.4	Synthetic self-assessment	110
9.2	Attractiveness	110
9.2.1	Scientific reputation and contributions	110
9.2.2	Staff hosting policy	112
9.2.3	Success in competitive calls for projects	112
9.2.4	Equipment quality and technological skills	112
9.2.5	Synthetic self-assessment	113
9.3	Scientific Production	113
9.3.1	Qualitative analysis	113
9.3.2	Potential and dissemination strategy	115
9.3.3	Scientific integrity, ethics and open science	116
9.3.4	Synthetic self-assessment	116
9.4	Contribution of Research Activities to Society	116
9.4.1	Socioeconomic partnerships and interactions	117
9.4.2	Research valorization and transfer	119
9.4.3	Science popularization	120
9.4.4	Synthetic self-assessment	120
10	Self-assessment of C2 team	122
10.1	Profile, Resources and Organization	122
10.1.1	Scientific objectives	122
10.1.2	Resources	125
10.1.3	Human resources management, safety, environment, ethical protocols, data and scientific heritage protection	126
10.1.4	Synthetic self-assessment	126
10.2	Attractiveness	126
10.2.1	Scientific reputation and contributions	126
10.2.2	Staff hosting policy	127
10.2.3	Success in competitive calls for projects	127
10.2.4	Synthetic self-assessment	127
10.3	Scientific Production	128
10.3.1	Qualitative analysis	128
10.3.2	Synthetic self-assessment	130
10.4	Contribution of Research Activities to Society	130
10.4.1	Socioeconomic partnerships and interactions	131
10.4.2	Research valorization and transfer	131
10.4.3	Science popularization	131
10.4.4	Synthetic self-assessment	132
11	Self-assessment of DIG team	133
11.1	Profile, Resources and Organization	133
11.1.1	Scientific objectives	133
11.1.2	Resources	133
11.1.3	Human resources management, safety, environment, ethical protocols, data and scientific heritage protection	134
11.1.4	Synthetic self-assessment	134
11.2	Attractiveness	134
11.2.1	Scientific reputation and contributions	134
11.2.2	Staff hosting policy	136
11.2.3	Success in competitive calls for projects	136
11.2.4	Synthetic self-assessment	136
11.3	Scientific Production	136
11.3.1	Qualitative analysis	136
11.3.2	Scientific integrity, ethics and open science	139

11.3.3 Synthetic self-assessment	139
11.4 Contribution of Research Activities to Society	139
11.4.1 Socioeconomic partnerships and interactions	139
11.4.2 Research valorization and transfer	140
11.4.3 Science popularization	140
11.4.4 Synthetic self-assessment	140
12 Self-assessment of DIVA team	141
12.1 Profile, Resources and Organization	141
12.1.1 Scientific objectives	141
12.1.2 Resources	141
12.1.3 Human resources management, safety, environment, ethical protocols, data and scientific heritage protection	142
12.1.4 Synthetic self-assessment	143
12.2 Attractiveness	143
12.2.1 Scientific reputation and contributions	143
12.2.2 Staff hosting policy	144
12.2.3 Success in competitive calls for projects	144
12.2.4 Equipment quality and technological skills	145
12.2.5 Synthetic self-assessment	145
12.3 Scientific Production	145
12.3.1 Qualitative analysis	145
12.3.2 Potential and dissemination strategy	146
12.3.3 Scientific integrity, ethics and open science	146
12.3.4 Synthetic self-assessment	146
12.4 Contribution of Research Activities to Society	147
12.4.1 Socioeconomic partnerships and interactions	147
12.4.2 Research valorization and transfer	147
12.4.3 Science popularization	147
12.4.4 Synthetic self-assessment	147
13 Self-assessment of QURIOSITY team	148
13.1 Profile, Resources and Organization	148
13.1.1 Scientific objectives	148
13.1.2 Resources	148
13.1.3 Human resources management, safety, environment, ethical protocols, data and scientific heritage protection	149
13.1.4 Synthetic self-assessment	150
13.2 Attractiveness	150
13.2.1 Scientific reputation and contributions	150
13.2.2 Staff hosting policy	151
13.2.3 Success in competitive calls for projects	151
13.2.4 Equipment quality and technological skills	152
13.2.5 Synthetic self-assessment	152
13.3 Scientific Production	153
13.3.1 Qualitative analysis	153
13.3.2 Potential and dissemination strategy	154
13.3.3 Scientific integrity, ethics and open science	155
13.3.4 Synthetic self-assessment	155
13.4 Contribution of Research Activities to Society	155
13.4.1 Socio-economic partnerships and interactions	155
13.4.2 Research valorization and transfer	156
13.4.3 Science popularization	156
13.4.4 Synthetic self-assessment	156

14 Self-assessment of RMS Team	157
14.1 Profile, Resources and Organization of the Team	157
14.1.1 Scientific Objectives	157
14.1.2 Resources	157
14.1.3 Team's functioning	159
14.2 Attractiveness	159
14.2.1 Scientific attractiveness	159
14.2.2 Team hosting policy	159
14.2.3 Calls for projects	160
14.2.4 Synthetic self-assessment	160
14.3 Scientific Production	160
14.3.1 Architectures, protocols and services for future networks	161
14.3.2 Virtualization and Automation in Network and Cloud environments	162
14.3.3 Models and algorithms for future networks	163
14.4 Contribution of Research Activities to Society	168
14.4.1 Socio-economic partnerships and interactions	168
14.4.2 Products for the cultural, economic and social world	168
14.4.3 Science popularization	168
15 Self-evaluation of IMAGES team	170
15.1 Profile, Resources and Organization	170
15.1.1 Scientific objectives	170
15.1.2 Resources	171
15.1.3 Human resources management, safety, environment, ethical protocols, data and scientific heritage protection	171
15.1.4 Synthetic self-evaluation	172
15.2 Attractiveness	172
15.2.1 Scientific reputation and contributions	172
15.2.2 Staff hosting policy	173
15.2.3 Success in competitive calls for projects	173
15.2.4 Synthetic self-evaluation	174
15.3 Scientific Production	174
15.3.1 Qualitative analysis	174
15.3.2 Potential and dissemination strategy	178
15.3.3 Scientific integrity, ethics and open science	178
15.3.4 Synthetic self-evaluation	178
15.4 Contribution of Research Activities to Society	178
15.4.1 Socioeconomic partnerships and interactions	178
15.4.2 Research valorization and transfer	179
15.4.3 Science popularization	179
15.4.4 Synthetic self-evaluation	179
16 Self-assessment of MM team	180
16.1 Profile, Resources and Organization	180
16.1.1 Scientific objectives	180
16.1.2 Resources	180
16.1.3 Human resources management, safety, environment, ethical protocols, data and scientific heritage protection	181
16.1.4 Synthetic self-assessment	182
16.2 Attractiveness	182
16.2.1 Scientific reputation and contributions	182
16.2.2 Staff hosting policy	183
16.2.3 Success in competitive calls for projects	183
16.2.4 Equipment quality and technological skills	184

16.2.5 Synthetic self-assessment	184
16.3 Scientific Production	184
16.3.1 Qualitative analysis	184
16.3.2 Potential and dissemination strategy	187
16.3.3 Scientific integrity, ethics and open science	187
16.3.4 Synthetic self-assessment	187
16.4 Contribution of Research Activities to Society	188
16.4.1 Socioeconomic partnerships and interactions	188
16.4.2 Research valorization and transfer	188
16.4.3 Science popularization	189
16.4.4 Synthetic self-assessment	189
17 Self-assessment of S²A team	190
17.1 Profile, Resources and Organization	190
17.1.1 Scientific objectives	190
17.1.2 Resources	191
17.1.3 Synthetic self-assessment	192
17.2 Attractiveness	193
17.2.1 Scientific reputation and contributions	193
17.2.2 Staff hosting policy	194
17.2.3 Success in competitive calls for projects	194
17.2.4 Equipment quality and technological skills	195
17.2.5 Synthetic self-assessment	195
17.3 Scientific Production	195
17.3.1 Qualitative analysis	195
17.3.2 Potential and dissemination strategy	204
17.3.3 Scientific integrity, ethics and open science	204
17.3.4 Synthetic self-assessment	204
17.4 Contribution of Research Activities to Society	205
17.4.1 Socioeconomic partnerships and interactions	205
17.4.2 Research valorization and transfer	205
17.4.3 Science popularization	206
17.4.4 Synthetic self-assessment	206
III UNIT TRAJECTORY	207
18 Trajectory of the LTCI	208
18.1 Research dynamics and ambition	208
18.1.1 Teams research dynamics and ambition	210
18.2 Organisation and development strategy	218
18.2.1 Teams organization and development strategy	219
19 Bibliography	221
IV Appendix	273
20 Teams financial resources	274
20.1 Communications and Electronic department	274
20.2 Computer Science and Networks department	276
20.3 Image, Data and Signal department	278

Part I

**GENERAL INFORMATION &
PORTFOLIO INTRODUCTION**

Chapter 1

General information

1.1 Unit identification

- Unit Name: Laboratoire Traitement et Communication de l'Information
- Acronym: LTCI
- Main scientific field: Science and Technology
- Scientific panels (in the Hcéres classification) by descending order of importance:
 - ST6: Sciences et Technologies de l'information et de Communication
 - * ST6_1 Informatique
 - * ST6_2 Génie électrique, électronique, électromagnétique, photonique et systèmes
 - * ST6_3 Signal, image, automatique, robotique et génie industriel
- Executive team:
 - Talel Abdessalem, director
 - Romain Alléaume, deputy director, research delegate of INFRES department
 - Van-Tam Nguyen, deputy director, head of COMELEC department
 - Florence Tupin, deputy director, head of IDS departament
 - François Roueff, head of doctoral studies
- List of the research unit's supervisory institutions and bodies:
 - Télécom Paris, Institut Mines-Télécom
 - Institut Polytechnique de Paris
- Doctoral schools of affiliation:
 - Ecole Doctorale de Mathématiques Hadamard (EDMH)
 - Ecole Doctorale de l'Institut Polytechnique de Paris (ED IP Paris)

1.2 Presentation of the LTCI

1.2.1 History, location of the unit

The LTCI (Laboratoire Traitement et Communication de l'Information) is a laboratory of Télécom Paris. It extends, since January 2017, the work carried out within the UMR LTCI (Unité Mixte de Recherche), a joint research laboratory with the CNRS (Centre National de la Recherche Scientifique). Established in 1982 (see Table 1.1), the LTCI is characterized by its broad coverage

of the field of information and communication science and technology. Its research activities range from the hardware layer (electronics, optoelectronics, system on chip, antennae, microwaves ...) to the software layer (systems, algorithms, protocols ...), and applied mathematics (graph theory, optimization, probabilities, statistics ...). These activities encompass studies on different kinds of data (audio, video, images, semi-structured data, and text) as well as works on network performance and services, or quantum information and cryptography. The laboratory is located in the premises of Télécom Paris, 19 place Marguerite Perey, 91123 Palaiseau, with one team (LabSoC) located at the Eurecom campus in Sophia Antipolis.

Date	Founding institutions	Status	Scope	Director
1982	ENST, CNRS	ERA	Communications & Signal Processing	C. Guéguen
1994	ENST, CNRS	URA 820, UMR 5152	Communications & Signal Processing	J.-P. Tubach
2003	Télécom Paris, CNRS	UMR 5141	ICT ^a & Social sciences	H. Maître
2013	Télécom Paris, CNRS	UMR 5141	ICT	O. Cappé
2016	Télécom Paris, CNRS	FRE	ICT	O. Cappé
2017	Télécom Paris	TP laboratory	ICT	T. Abdesslem

TABLE 1.1: Main steps in the history of the LTCI.

^aInformation and Communication Technology

1.2.2 Structure of the unit

The organizational chart of the LTCI is shown in Figure 1.1. The LTCI is composed of fifteen research teams spread over three departments. Each team is headed by a faculty appointed by the laboratory director upon proposal from the members of the team. Each department is managed by the department head who is the line manager of all the academic staff in his department. The department's mission is to coordinate the activity of the teams composing it, in terms of teaching, research and development. The LTCI is managed by an executive team, assisted by a laboratory council and a scientific council. For the internal regulations and statutes of the LTCI, see chapter 20.3, in the Appendix.

Communications and Electronic department (Van-Tam Nguyen). The Communications and Electronics department (COMELEC) headed by Van-Tam Nguyen focuses on the physical and material foundations of smart algorithmic processing of signals and data, and their insertion into a global information system, as well as on the design/modeling/integration of objects into the intelligent information system. The department hosts six teams of the LTCI, which bring together Télécom Paris research in the field of communications and electronics. The LabSoC team is located in Sophia Antipolis, on the EURECOM site.

- Circuits and Communication Systems (C2S), headed by Patricia Desgreys
- Digital Communications (ComNum), headed by Ghaya Rekaya
- Optical Communications (GTO), headed by Frédéric Grillot
- Systems on Chip (LabSoC), headed by Ludovic Aprville
- Radio-Frequencies, Micro and Millimeter Waves (RFM²), headed by Xavier Begaud
- Secure and Safe Hardware (SSH), headed by Lirida Naviner

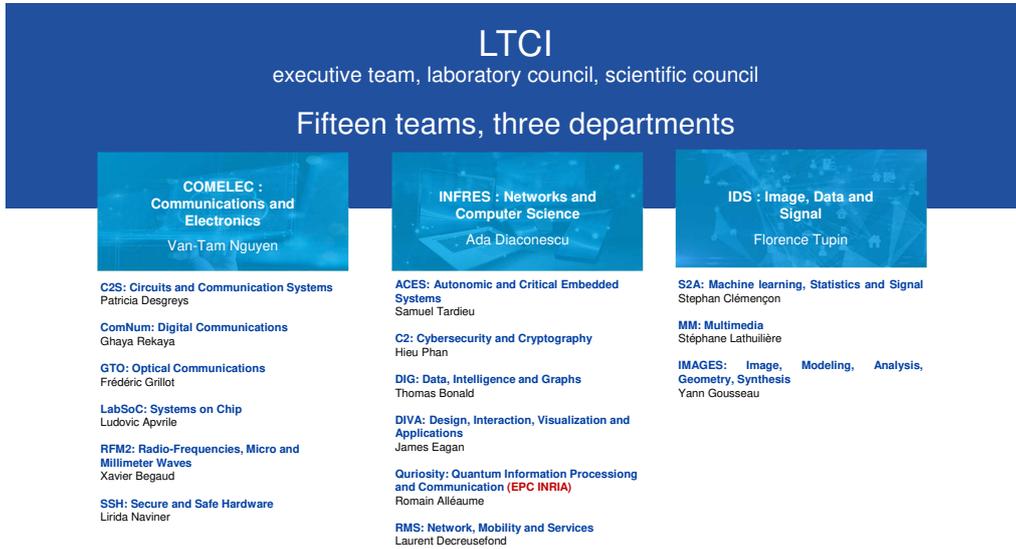


FIGURE 1.1: Organizational chart of the LTCI.

Computer Science and Networks department (Ada Diaconescu). The Networks and Computer Science department (INFRES), headed by Ada Diaconescu, focuses on various aspects of computer science (e.g., autonomous, embedded and real-time systems, distributed systems, data management and mining, human-computer interaction, cybersecurity, cryptography, quantum information processing) and networks (e.g. performance evaluation, network control and monitoring, design of innovative network services).

The department hosts six LTCI research teams:

- Autonomous and Critical Embedded Systems (ACES), headed by Samuel Tardieu
- Cybersecurity and Cryptography (C2), headed by Dong Hieu Phan
- Data, Intelligence and Graphs (DIG), headed by Thomas Bonald
- Design, Interaction, Visualization and Applications (DIVA), headed by James Eagan
- Quantum Information Processing and Communications (QURIOSITY), joint Inria – IP Paris team, headed by Romain Alléaume
- Network, Mobility and Services (RMS), headed by Laurent Decreusefond

The department also hosts the Research Engineering Cell (CIR) headed by Nicolas Bouché – this is a special-purpose team offering technical support to research and development activities. In particular, this team manages the laboratory’s computer clusters and research network infrastructure.

Image, Data and Signal department (Florence Tupin). The Image, Data and Signal department (IDS), headed by Gaël Richard (-2022), then by Florence d’Alché (2022-2023), and now by Florence Tupin (2023-) covers many aspects of artificial intelligence, data science and visual and audio computing (statistics, optimization, machine learning, signal and image processing,

computer vision, computer graphics, video coding, audio applications, NLP, medical imaging, remote sensing ...).

The department hosts three LTCI research teams covering the following topics:

- Machine learning, Statistics and Signal (S²A) team, headed by Stephan Cléménçon
- Multimedia (MM), headed by Stéphane Lathuilière
- Image, Modeling, Analysis, Geometry, Synthesis (IMAGES), headed by Yann Gousseau

1.2.3 Platforms, equipment, and shared services

In this section, we give an overview of the equipment and platforms available to the laboratory researchers. We start with the computing resources made available to all the researchers, then we present more succinctly the main platforms and other equipment managed by the teams. The aim is to give the reader an idea of both the diversity of these equipment and their importance for laboratory research activity. Note that the laboratory took advantage of Télécom Paris' move to new premises on the Palaiseau campus to renew a large part of its equipment and install its platforms in spacious premises, more suited to their proper functioning. The laboratory was also able to set up ZRRs (Restricted Areas, 4 in total) for the teams working on sensitive topics (cybersecurity, hardware/software security, 5G and next generation networks ...), in particular in case of joint work with an industrial partner.

Shared computer clusters and research network infrastructure.

The CIR engineering unit provides a set of computing resources for research. These resources are composed of CPU (physical and virtualized), GPU (graphics processor), and network, all made up of rack servers installed in a dedicated servers' room equipped with a cooling system (liquid-cooling) for energy efficiency.

For the physical CPU part, there are **24 high-performance servers** accessible to users directly via *ssh* with their Télécom Paris accounts. A total of **1500 threads** and **10 TB** of memory are available. As an example, we have a server that has 128 Threads and 1 TB of Memory (RAM). User data can be stored locally but is more generally stored on a fast **80 TB storage server** (NFS) (solid state drive) connected with a 40 Gbit/s link. Virtualized CPU (vCPU) computing resources are also available through our OpenStack cloud platform¹. This platform allows users to create virtual machines through a web application dedicated to their team. In total, more than 1024 VMs (medium type) can be started, and distributed across 15 servers. This platform also allows the users to simply deploy Kubernetes clusters². Note that the applications deployed on the VMs of our OpenStack can be accessible, from inside and outside Télécom Paris, via the internet.

For GPU resources, we have 9 servers accessible in the same way as the CPU servers. These servers are equipped with NVIDIA cards of different generations. In total, we have, for this part, 14 K80 cards, 6 V100 cards, and **9 A100 cards**. With the particular aim of optimizing the utilization rate of our GPU resources, we have implemented a Slurm scheduler³ for the second part of our GPU resources made up of 27 NVIDIA P100 cards, 16 NVIDIA V100 cards, 32 NVIDIA A40 cards and **33 NVIDIA A100 cards**. Today, we have **187 users** of this GPU cluster (i.e., more than half of the laboratory's researchers, including doctoral students and postdocs). A network storage system (NFS) is also available for the GPU servers. This system is made up of **4 servers** offering a storage capacity of **433 TB** (HDD mechanical disks) and an ultra-fast storage capacity of **192 TB**. These servers are connected to the cluster network with 100 Gbit/s Ethernet links.

Concerning network resources, the CIR engineering unit manages also a special network for research purposes (called R2). It is used by our OpenStack cloud platform, and also directly by the

¹<https://www.openstack.org/>

²<https://docs.openstack.org/magnum/>

³<https://slurm.schedmd.com/>

LTCI researchers. In particular, it enables the carrying out of experiments requiring high network performance such as 5G. This network operates in high availability, it is made up of 2 firewalls (10 Gbits/s), 2 routers (100 Gbits/s), 5 switches (100 Gbits/s), and 6 switches (10 Gbits/s). These resources are supervised for alert management with several Nagios servers and for the usage rate part by the Prometheus/Grafana monitoring system.

Table 1.2 lists the main laboratory equipment and platforms managed by the LTCI teams. An almost exhaustive list of software platforms developed by the LTCI teams, and open software projects to which LTCI members contribute actively, can be found on the web page of the LTCI COSI⁴ (Center for Open Software Innovation). Some of them appear in the portfolio of the laboratory (GPAC, Software Heritage, RAMSES, Webstrates, YAGO, River, Scikit-network), and others are well described in the self-assessment chapter of the teams. The objectives of the COSI are as follows 1/ to present the open-source projects created and co-created at LTCI; 2/ to promote open development practices in computing as an important part of the open science movement; 3/ to promote open-source software and models in academia and in general; 4/ to raise awareness among researchers and the public and provide relevant information to interested parties; 5/ to provide the best possible support for open-source software development communities (OSS).

Acronym	Description	Team
Optical Com. Lab	High-performance signal generation and characterization tools enable a diverse range of experiments, including high-capacity transmission, quantum key distribution, novel optical devices, free space optics, and optical fiber sensing. The laboratory is well-appointed with lasers, amplifiers, detectors, modulators, spectrometers, pattern generators, error detectors, and other essential equipment for near- and mid-infrared data communications. With all its advanced instruments, the team has developed and maintained multiple leading-edge research platforms (see chapter 5, section 5.1.3).	GTO
RF wave characterization Lab	Equipped with 2 anechoic chambers allowing antenna characterization up to 170 GHz, a probe station dedicated to the source pull/load pull nonlinear characterization of millimeter wave (40 – 60 GHz) power amplifiers. As part of the nonlinear characterization of GaN components or power amplifiers in millimeter wave frequencies, a collaboration was set up with the III-V Lab to carry out nonlinear source pull/load-pull characterization of power amplifiers in the 40 – 60 GHz range. This platform is unique in the research environment of Saclay and Palaiseau. See chapter 7, section 7.2.4 for more details.	RFM ²
Trust Analysis Lab	This laboratory hosts the Trust Analysis Platform (TAP), which is an important tool for practical analysis of the robustness of digital circuits, either by probing physical phenomena or injecting disturbances to create faults. See chapter 8, section 8.2.4 for more details.	SSH, C2S
Free 5G	This platform aims to enable the design, development, and evaluation of new network functionalities in a software radio environment. It is installed in a ZRR equipped with a Faraday cage (40 square meters), in which a complete 4G/5G system is deployed. See chapter 14, section 14.1.2 for more details.	RMS

⁴<https://www.telecom-paris.fr/en/research/labs/information-processing-ltci/open-software-innovation>

FIT IoT-Lab	This platform provides a facility suitable for testing networking with small wireless sensor devices and heterogeneous communicating objects. See chapter 14, section 14.1.2 for more details.	RMS
-------------	--	-----

TABLE 1.2: Main laboratory equipment.

Shared services. In addition to technical support services for research, administrative staff are made available to the teams by Télécom Paris. Physically located in the departments (near the teams), these administrative units (generally made up of an administrative manager and two to three assistants) manage all administrative tasks linked to the research activity of laboratory members (hiring non-permanent staff, purchasing requests, mission order requests, budget monitoring, etc.). These administrative units (10 persons, spread over three units) manage the interaction between researchers and the various centralized services of the school (HR, Finance, Legal Department, Contracts and Intellectual Property, etc.). A scientific communication service (two people) is also provided to the teams as well as a project manager who devotes half of her time to the LTCI. The latter notably assists the Director of the laboratory in organizing and monitoring the work of the laboratory governance bodies.

1.2.4 Size and composition of the teams

Table 1.3 summarizes the composition of the teams as it was at the end of December 2023. More details can be found in the self-assessment chapter of each team.

Acronym	Name	Size at 31/12/2023 (permanent staff)	
		Faculty	Engineers
C2S	Circuits and Communication Systems	5	0.5
ComNum	Digital Communications	6	
GTO	Optical Communications	8	1
LabSoc	Systems on Chip	4	
RFM ²	Radio-Frequencies, Micro and Millimeter Waves	7	1.5
SSH	Secure and Safe Hardware	10	2
ACES	Autonomous and Critical Embedded Systems	13	
C2	Cybersecurity and Cryptography	10	1
DIG	Data, Intelligence and Graphs	9	1
DIVA	Design, Interaction, Visualization, and Applications	5	1
QURIOSITY	Quantum Information Processing and Communications	4	
RMS	Network, Mobility and Services	10	2
IMAGES	Image, Modeling, Analysis, Geometry, Synthesis	11	1
MM	Multimedia	5	1
S ² A	Machine learning, Statistics and Signal	20	
	Computer clusters and research network infrastructure		1
Total		127	13

TABLE 1.3: Teams composition.

1.2.5 Scientific orientations of the unit and its teams

The LTCI is a laboratory of Télécom Paris (Institut Mines-Télécom) and one of the main laboratories of Institut Polytechnique de Paris (IP Paris) in the field of Computer and Communication

Sciences (in other words, Information and Communication Science), in terms of size and scientific production. Its mission is to contribute, by the excellence of its research, to the advancement of knowledge in the field of information sciences and the development of the potential of French innovation in the digital domain.

Fully integrated into IP Paris, the LTCI is very active in three of its disciplinary teaching and research departments:

- Computer Science, Data and Artificial Intelligence (IDIA) department, led by Bruno Defude (Samovar, Télécom SudParis), with 73 members from the LTCI out of 209⁵;
- Information, Communication, and Electronics (ICE) department, led by Bruno Thedrez (LTCI, Télécom Paris), with 32 members from the LTCI out of 53;
- Mathematics (Math) department, led by Franck Pacard (CMLS, Ecole Polytechnique), 14 members from the LTCI out of 146.

The LTCI aims to contribute to some of the major objectives of IP Paris, namely the development of scientific research at the highest level, the strengthening of the PhD Program, the emergence of interdisciplinary research, and the development of the innovation potential and transfer to the industry.

The LTCI is then strongly involved in the Hi! PARIS (AI & Data) interdisciplinary center, where members of the LTCI (mainly from the S²A team) are involved in its governance and its scientific committee. The LTCI is also involved actively in three other interdisciplinary centers of IP Paris: E4H (Engineering for Health), E4C (Energy for Climate), and CIEDS (Centre for Defence and Security).

IP Paris has a unique position in France in Computer and Communication Sciences, with a large community of more than 300 permanent faculty, and more than 1000 total staff. Whatever the intended applications, the researchers in this domain produce and apply theories and models devised to explain better, as well as to improve performance, security, and safety. Simultaneously, models should allow for better and more efficient large-scale data treatment, implementing security through privacy certificates, etc. Computer and Communication Sciences are a very peculiar branch of science in which "theory" and "practice" are intertwined, with rapid paths to and from theory. The work initiated in 2021 for the definition of a common vision of the scientific expertise and challenges of IP Paris in this domain, led to the definition of the following scientific axes, in which the research subjects of the LTCI teams are fully integrated:

- **Data Science & Artificial Intelligence** (Axis 1)
- **Visual and Audio Computing, Interaction** (Axis 2)
- **Digital Trust** (Axis 3)
- **Next Generation Digital Infrastructures**
A large number of the LTCI teams have their research activity in this area. For more homogeneity in the composition of the axis and a finer vision of the teams' activity, we have chosen at LTCI to split this axis into two sub-domains:
 1. **Embedded Systems** (Axis 4)
 2. **Communication Systems & Networks** (Axis 5)
- **Mathematics & Applications** (Axis 6)

Table 1.4 indicates on which axis the laboratory teams are working. Large blue bullets indicate the main axis in which the team's activity falls. The black bullets indicate a possible secondary

⁵IP Paris statistics, 2021.

axis of the team’s activity. For readability reasons, we put a maximum of three bullets on each line (the main axis, plus two possible secondary axes). The sixth axis (Mathematics & Applications) is a transversal axis since no team has it as a main axis. The description of these axes is given below, in section 1.3.

Acronym	Axis 1	Axis 2	Axis 3	Axis 4	Axis 5	Axis 6
C2S				•	•	
ComNum			•		•	•
GTO					•	
LabSoC			•	•		
RFM ²					•	
SSH			•	•		
ACES			•	•		
C2			•		•	•
DIG	•					
DIVA		•				
QURIOSITY			•		•	•
RMS					•	•
IMAGES	•	•				•
MM	•	•				
S ² A	•	•				•

TABLE 1.4: Teams scientific orientations.

1.3 Scientific subjects and their implications

Today’s society is digitalized. From smart grids to nuclear plants, commercial airplanes to the long-awaited autonomous cars, the web and communication networks, imaging, data analysis, and AI applications in all industries (finance, health, security, etc.), there is no single aspect of our everyday life that is not relying on computer science advances. The fundamentals of computer science, mathematical modeling, and information theory are what gather the computer and communication sciences community at IP Paris, whatever their intended applications are. Scientists in this domain use and produce theories and models that should better explain, and improve performances, security, and safety, and should allow for better treatments of data, at scale, with privacy certificates. Indeed, computer science is a very peculiar science in which "theory" and "practice", are intertwined and complement each other.

The LTCI is completely aligned with this vision which can be even found in the composition of the teams, which often bring together expertise on theoretical and practical aspects of the research subjects they work on. As mentioned before, the main research subjects of the LTCI can be summarized in the following axis.

1.3.1 Data Science & Artificial Intelligence

Be it for prediction, decision, or interpretation purposes, the processing of data collected using modern technologies raises a wide variety of issues, related to their nature (e.g., massive, heterogeneous, sparse, etc.) and complexity (e.g., high-dimensional, unstructured, uncertain, etc.), to design more "intelligent" machines/devices (artificial intelligence). Our teams work on advanced topics ranging from computational aspects of data science, and machine learning, to probabilistic modeling and mathematical statistics, through optimization, with a special emphasis on visual and audio data processing and, recently, on embedded AI. In the following, we give an overview of the topics covered by the main contributing teams to this axis.

- The DIG (Data, Intelligence and Graphs) team’s research subjects are within the computational aspects of data science, machine learning, and artificial intelligence. Its objectives are to make knowledge easy to extract (especially from textual sources), to store, to process, to query, and to understand by machines. More precisely, the expertise of the team covers topics ranging from database theory to graph mining, machine learning, natural language processing, knowledge bases, machine reasoning, and collective intelligence.
- The S²A team is focusing on the development of algorithms and concepts for AI. Its main expertise is in probabilistic modeling and mathematical statistics, machine learning and optimization, audio data analysis and signal processing, and social computing. It aims to produce sound methodological research in these domains, in response to the challenges raised by the nature (volume, availability, reliability, etc.) and complexity of data.

1.3.2 Visual and Audio Computing, Interaction

The research topics of this axis share several key aspects, since they all span from the acquisition or generation of complex, multimedia content, through the analysis and processing of such content, and to the design of new interaction methodologies with the environment or the users. The LTCI has strong expertise in visual and audio computing, as well as in computer graphics and Human-Computer Interaction.

In the following, we give an overview of the topics covered by the main contributing teams to this axis.

- The DIVA (Design, Interaction, Visualization & Applications) team focuses on the fundamental and applied research of human-computer interaction (HCI). This research is characterized by a two-fold challenge: representing and interacting with ever larger quantities of data and achieving this not just on standard computers but also on small mobile and non-traditional devices. Its main contributions are in innovative interactions (techniques, physical artifacts, and software paradigms), data visualization, sense-making, and behavior models.
- The IMAGES (Image, Modeling, Analysis, GEometry, Synthesis) team carries out research in image analysis and understanding, computer vision, and 3D computer graphics, covering the entire spectrum of the modeling, analysis, transformation, representation, interpretation and synthesis of images, 3D and digital objects. The team focuses on the modeling of images, tri-dimensional and numerical objects, with the development of mathematical models, ranging from physical acquisition to high-level interpretation, and artificial intelligence models (spatial reasoning, knowledge representation). The team has also strong expertise in computer graphics for geometric modeling, image synthesis, virtual reality, and 3D interactive systems. Its preferred application domains are medical imaging, remote sensing imaging, computational photography, and creative industries.
- The MM (Multimedia) team subjects are primarily in two areas: transmission of multimedia data, and efficient deep learning for visual and multimodal data. On one hand, the team has internationally recognized expertise in data transmission which is original (nationwide) and crucial to preserve, notably due to their significant industrial impact. On the other hand, the team has developed promising expertise in deep learning for multimodal data, achieving notable results in this area.

1.3.3 Digital Trust

Digital trust is about dependability, i.e. the conjunction of reliability, safety, availability, maintainability, and cybersecurity properties. New hardware (based on complex multi-core architectures) leads us to study novel fundamental modeling techniques, testing algorithms, and formal methods to cope with the more involved non-deterministic behavior of the hardware and corresponding algorithms, and to allow the practical use of this new computation power in critical applications, such as embedded control systems and CPS (Cyber-Physical Systems).

In the following, we give an overview of the topics covered by the main contributing teams to this axis.

- The C2 (Cybersecurity and Cryptography) team is devoted to research in cybersecurity and cryptography and their interactions. Cryptography is a fundamental cornerstone of cybersecurity, traditionally supporting data confidentiality, integrity, and authenticity. The team is also working on tailored approaches to security that can meet the broad range of security requirements and provide adaptive security systems.
- The QURIOSITY (Quantum Information Processing and Communication) team intends to embrace a relatively wide area of theoretical questions, ranging from quantum cryptography, which the team ambition to combine with complexity-based schemes and establish as a framework to enhance hardware security, to the mathematical foundations of quantum information and quantum computing. On the other side, the team also intends to develop research capable of leveraging photonics and digital information processing technologies to design systems capable of producing high-dimensional and controllable quantum states of light to push forward the frontiers of quantum information processing advantage.

1.3.4 Embedded Systems

In this axes, we aim to propose digital architecture and methods to build efficient and reliable embedded systems relying on reliable and secure hardware and software components. The motivation is fueled by emerging new applications that come with stringent and orthogonal constraints, such as trust, high performance, low energy, and low cost. This is particularly true for applications like 5/6G, autonomous cars, smart cities, e-health, edge computing, and embedded AI.

In the following, we give an overview of the topics covered by the main contributing teams to this axis.

- The ACES (Autonomous Critical Embedded Systems) team is positioned at the intersection of Computer Science and Electrical Engineering, with a focus on developing resilient, secure, and efficient digital systems that tackle the challenges of integrating digital and physical worlds. Their work encompasses enhancing cybersecurity and privacy through advanced cryptographic measures and defense mechanisms, aiming to establish trust in digital interactions. A significant part of the team's work is dedicated to the advancement of complex, embedded, and distributed systems that play pivotal roles in modern infrastructures, seeking to improve their performance, fault tolerance, and reliability. Through its fundamental research in consensus algorithms, multiparty computation, and modeling languages, alongside efforts to refine software engineering practices, the team endeavors to create sophisticated systems and software that meet the evolving needs of society and technological infrastructure.
- The LabSoC team's expertise is in the design and verification of embedded systems, with a focus on the safety, security, and performance of these systems. The team develops new methods, languages, and verification techniques that can tackle the specificities of modern embedded systems. This includes the handling of cyber-threats targeting these systems (external attacks, internal attacks, including side-channel attacks), and how cyber-threats, and their countermeasures, could impact the safety and performance of these systems. Verification techniques developed by the LabSoC team also refer to the safety and cybersecurity of these systems by adopting new incremental approaches to tackle the complexity and diversity of these systems.
- The SSH (Secure and Safe Hardware) team aims to propose digital architectures and methods to build efficient embedded systems relying on specific hardware or low-level software implementations. It places significant emphasis on addressing security and safety concerns to ensure the trustworthiness of the proposed architectures. Given the proliferation of threats that compromise privacy, cybersecurity, and system reliability, it is imperative to address vulnerabilities at both the software and hardware levels.

1.3.5 Communication Systems & Networks

This axis addresses multiple facets and challenges of the Communication Systems & Networks domain. Our work covers a wide spectrum of topics: future networking architectures, cloud computing and architecture, wireless communication, 5G/6G, IoT, optical communication, and quantum networking. Our expertise ranges from electronics to computer science and mathematical modeling.

In the following, we give an overview of the topics covered by the main contributing teams to this axis.

- The C2S team aims to develop circuits and systems for communication. Its expertise is in hardware implementation of analog and mixed-signal (AMS) systems enhanced by digital algorithms. The team develops high-performance RF power amplifiers, and innovative communications systems dealing with wideband transceivers, and works towards semantic communication by developing Analog-to-Feature (A2F) conversion (for wireless sensors network and IoT). The team also develops intra-body communication transceivers at low rates and very low power consumption, for health-care applications.
- The ComNum (Digital Communications) team is focusing its research work on gaining a better understanding of the fundamental limits of communication networks and devising the means to reach them. It is particularly active in point-to-point communications, network optimization, communications and device security, and interdisciplinary tools derived from information theory and statistics.
- The GTO (Optical Telecommunications) team conducts advanced research in high-rate fiber-optic transmission, optical network architectures, advanced lasers for communications, integrated photonics, and distributed optical fiber sensors. The team is particularly active in high-rate communications in short-reach and long-haul transmission systems, optical network architecture and cross-layer optimization, performance improvement in optical devices and systems for context-driven applications, and quantum optics, non-linear photonics, and laser dynamics.
- The RFM² (Radio Frequency, Microwaves, and Millimeter waves) team focuses on three key research areas: 1/ design of components and subsystems for the radio links involved in 5G, IoT, satellites, radar, localization, reliable and secured massive communications; 2/ mathematical modeling and formalization of both the behavior of components and subsystems and the interaction between waves and humans; 3/ development of innovative characterization methods of the performance of the microwave and millimeter wave components and systems.
- The RMS (Networks, Mobility and Services) team's research subjects revolve around issues concerning very large networks and operated systems. This involves, in particular, designing tomorrow's mobile networks and communications, the Internet of the Future, the Internet of Things, and developments in cloud computing and virtualization. The team members build models and metrology tools, design architectures and protocols, and develop algorithms and mathematical analysis methods for performance evaluation and network optimization.

1.3.6 Mathematics & Applications

This axis includes probabilities and statistics, optimization, information theory, stochastic geometry, algebraic geometry, number theory, combinatorial coding theory, and computational complexity. Mathematics is transversal to other scientific subjects in the sense that there are no teams specifically dedicated to a mathematical domain of research. Here are some examples:

- Algorithms in cryptography often rely on algebraic geometry or number theory;
- Network modeling requires theoretical tools in stochastic geometry and random fields;
- Digital communication is based on information theory and coding theory;

- Data sciences involve statistical modeling and inference, computational statistics and optimization;
- Quantum communications require a deep understanding of both quantum physics and mathematical physics.

The involvement in these areas of mathematics varies from necessary expertise for the team's main scientific subject to working at the forefront of the research activities of the field. The levels of commitment depend on the domain and the task force dedicated to this domain. Researchers working on certain specific mathematical fields come together within the team whose main scientific subject is closely linked to these fields.

Most of the research production in mathematics is concerned with statistics, probability, and optimization. Most of the 10 HDR members⁶ of the LTCI, affiliated with the mathematical doctoral school EDMH (Ecole doctorale mathématiques Hadamard), are working at least on one of these topics.

The LTCI was a member of the Labex LMH and is now part of the FMJH foundation. Around 20 faculty members are within the Department of Mathematics of IP Paris.

1.4 Resources

This section gives an overall vision of the financial and human resources (non-permanent researchers and interns) from which the unit took benefit to develop its projects during the evaluation period. Note that more than a thousand non-permanent researchers and interns were hired. The cumulative budget for the period is around €49.5M.

1.4.1 PhD, postdocs, research engineers and interns

	PhD	Postdocs & Engineers	Interns	Total
C2S	22	5	12	39
ComNum	40	15	5	60
GTO	50	14	18	82
LabSoC	12	6	6	24
RFM ²	19	17	20	56
SSH	26	5	8	39
ACES	41	16	44	101
C2	38	19	25	82
DIG	49	14	37	100
DIVA	12	2	5	19
QURIOSITY	12	2	6	21
RMS	39	25	27	91
IMAGES	80	15	39	134
MM	24	19	13	56
S ² A	119	49	62	230

TABLE 1.5: Non-permanent research staff (2018-2023).

1.4.2 Financial resources

We present here the financial resources of the unit aggregated by category (following the typology given by the Hcéres⁷). We first give a consolidated view of the resources at the level of the unit in

⁶Holders of a "Habilitation à Diriger des Recherches".

⁷In the document "Données de caractérisation de la production de l'unité".

table 1.6, then we give a consolidated view per department in tables 1.7, 1.8 and 1.9. The details of the financial resources per team can be found in the appendix 20 and in the chapters dedicated to the teams' self-assessments.

2018-2023 (K€)							
	2018	2019	2020	2021	2022	2023	Total
Public National	2,847	2,455	1,778	1,980	2,554	3,426	15,041
International	1,195	1,846	1,477	1,680	1,080	1,421	8,701
Partnership & Transfer	4,434	4,320	4,457	4,180	4,020	4,373	25,784
Total	8,477	8,621	7,712	7,841	7,655	9,220	49,526

TABLE 1.6: Global view of the financial resources of the unit.

2018-2023 (K€)							
	2018	2019	2020	2021	2022	2023	Total
Public National	639	478	433	411	394	983	3,339
International	532	947	740	746	433	874	4,272
Partnership & Transfer	1,441	1,706	1,663	850	1,122	1,180	7,962
Total	2,613	3,131	2,836	2,007	1,949	3,037	15,573

TABLE 1.7: Financial resources of the COMELEC department.

2018-2023 (K€)							
	2018	2019	2020	2021	2022	2023	Total
Public National	962	637	595	869	1,359	1,024	5,446
International	362	599	437	647	547	132	2,723
Partnership & Transfer	1,493	1,475	1,361	1,457	1,329	1,228	8,344
Total	2,817	2,712	2,393	2,973	3,235	2,384	16,513

TABLE 1.8: Financial resources of the INFRES department.

2018-2023 (K€)							
	2018	2019	2020	2021	2022	2023	Total
Public National	1,246	1,339	750	700	801	1,419	6,256
International	302	300	300	287	101	415	1,705
Partnership & Transfer	1,500	1,139	1,433	1,874	1,569	1,964	9,478
Total	3,048	2,778	2,483	2,861	2,471	3,798	17,439

TABLE 1.9: Financial resources of the IDS departement.

1.5 Activity profile

Activities (100 points distributed on 7 items)	
Contribution to innovative teaching based on research	
University Research School – EUR, structuring training through research – SFRI, etc.	7
Research administration	
Responsibility for steering research (VP, Institute Management, Scientific Director, etc.), participation in evaluation systems (CNU, CoNRS, CSS, etc.), responsibility for IdEx, project management (ANR, Horizon Europe, ERC, CPER State-Region contract, France 2030, etc.), editorial responsibilities in national or international journals or collections.	7
Research dissemination	
Sharing knowledge with the general public, scientific outreach, and interface between science/society.	3
Research and research supervision	
Involvement in supervision at the doctoral level and post-doctoral level.	60
Valorisation, transfer, innovation	20
Technical expertise	
For national and regional public authorities, businesses, and international bodies (UN, FAO, WHO, etc.).	3
Other activities	0

The LTCI profile is strongly anchored in fundamental research, research supervision, valorization, and transfer. Its scientific production remains at a very high level over time with an excellent publication profile, in volume and quality. The table 1.10 presents the evolution of the number of publications of the unit over the considered period. We observe in particular an impact of the COVID crisis, even if the volume of publications remains at a high level over the period (4 publications per EC per year, on average).

	2018	2019	2020	2021	2022	2023	Total
Article	150	177	168	190	171	134	990
In Conf. proceedings	396	339	276	282	298	281	1,872
Books, chapters and collections	28	35	22	42	18	22	167
Total	574	551	466	514	487	437	3 029

TABLE 1.10: Scientific production of the unit.

1.6 Research environment

Figure 1.2 gives a synthetic presentation of the research and innovation environment of the LTCI, at the site level (Orsay-Palaiseau-Saclay), at the regional level, and at the national level.



FIGURE 1.2: Research and innovation environment.

Figure 1.3 focuses on the main projects of Institut Polytechnique de Paris to which the LTCI contributes, as well as the shared projects (and entities) with the University of Paris Saclay to which the LTCI is also contributing.



FIGURE 1.3: Campus level research and innovation environment.

1.7 Consideration of the recommendations of the previous report

This section succinctly describes our understanding of the recommendations from the previous evaluation and the actions implemented to take these recommendations into account.

We denote by *Recommendation A* the recommendations of the jury of the previous assessment regarding research products and activities, by *Recommendation B* the recommendations concerning the organization and life of the unit and the teams, and by *Recommendation C* the recommendations concerning the five-year scientific outlook given at the previous evaluation.

1.7.1 Unit level recommendations

Recommendation A: *Le comité ne peut que recommander de poursuivre les travaux menant à l'excellence des productions tant en quantité qu'en qualité.*

Suite aux départs de nombreux chercheurs à temps plein, le laboratoire doit veiller à continuer à développer des travaux de recherche fondamentale soutenus, qui alimentent les transferts. Il doit rester attentif aux équipes de petite taille ayant subi des transformations structurelles importantes durant la période, en les accompagnant si nécessaire, soit en les renforçant soit en les regroupant.

The jury is referring here to the sudden departure of CNRS researchers (around twenty), following the conflict which arose in 2016 between the CNRS and Télécom Paris, concerning the governance of the unit. The LTCI was able to obtain enough job positions from Télécom Paris to maintain all its teams. Some have still had to refocus their activities on their remaining expertise and direct their recruitment based on that. This is for example the case for the MM, DIVA and IQA teams. The latter, now named QURIOSITY, has transformed into a joint team with Inria, thus benefiting from recruitment from Télécom Paris and Inria.

Concerning the development of fundamental research, the laboratory maintains its growth trajectory in this area and continues to monitor it. This can be verified by the quality of the recruitment carried out over the last period and the quality of the publications, particularly in AI and data sciences, in the field of digital trust, or communication systems and networks.

Recommendation B: *L'unité doit poursuivre les actions mises place ces deux dernières années*

dans l'organisation managériale de l'unité conduisant à des circuits de décision collégiale qui font l'adhésion des personnels.

L'unité doit poursuivre l'animation scientifique matricielle mise en place, le comité recommande d'y associer des moyens humains dédiés. De même, des moyens spécifiques comme des financements de thèse pourraient être réservés à des sujets transverses s'inscrivant dans un des axes scientifiques et proposés par des membres de deux équipes ou de deux départements différents.

The LTCI has, since 2020, two governance bodies (see the statutes and internal regulations of the Unit in the appendix to this report), a Scientific Council which brings together all the team leaders, and a Laboratory Council which brings together the representatives of all staff. These bodies meet every two months, on an alternating basis. In addition, the laboratory director has a regular meeting each week with the heads of the departments or their representative for research, where they can exchange information and discuss everything that concerns the functioning of the laboratory.

Regarding cross-domain scientific animation, the laboratory has dedicated part of its budget to the organization of cross-domain seminars (for instance, the Data Science Seminar). But the result is still not satisfactory. We have not yet explored the idea of having dedicated staff for this task. This is probably what we should try to do in the next period.

Recommendation B: *L'unité doit s'interroger sur le risque d'isolement de l'équipe située à Sophia Antipolis et réfléchir à des stratégies (intégration plus forte au laboratoire, intégration plus forte dans l'environnement niçois).*

Télécom Paris will soon no longer have engineering students trained at Eurecom, which is now recruiting through the same competition as Télécom Paris (Mines-Télécom competition). Relations between Télécom Paris and Eurecom are therefore changing in nature, but the LTCI team based in Sophia Antipolis (LabSoC) continues to have teaching activity at Eurecom and research collaborations with various local partners, including Eurecom, Inria, and companies based in the region. The team also strengthened its collaborations with the LTCI teams based in Palaiseau, notably SSH, through thesis co-supervision and its involvement in joint research projects (for example, PEPR *5G et Réseaux du Futur*, PEPR *Cybersécurité* and the ICMS⁸ chair led by Van-Tam Nguyen).

Recommendation B: *Plus ponctuellement, concernant le déménagement à Saclay, l'accompagnement des doctorants et post doctorants du laboratoire doit être renforcé, en particulier en anticipant d'éventuelles difficultés pour les doctorants qui travaillent sur des plateformes qui seront rendues indisponibles momentanément. Une réflexion commune avec les directeurs de thèse doit être engagée très rapidement pour identifier les difficultés potentielles bien en amont et proposer des solutions adaptées, comme par exemple prévoir le séjour de ces doctorants dans d'autres laboratoires en France ou à l'étranger. Il faudra veiller aussi à ce que la vie du laboratoire ne soit pas trop impactée par le développement du télétravail, qui sera potentiellement augmenté du fait de l'éloignement des personnels (toute catégorie) de leur domicile.*

Le site web du laboratoire doit être actualisé.

Regarding the move of the platforms to the new building and their availability, everything went well and no problem seriously impacted the progress of the research work of the teams and their doctoral students.

Regarding laboratory life, the pandemic which arrived just following the move and the transition to 3 days of teleworking for a large part of the staff undeniably had an impact, but fortunately no significant impact on its scientific production. The issue of teleworking does not specifically

⁸Cybersécurité intelligente pour les systèmes de mobilité – <https://www.telecom-paris.fr/cybersecurite-intelligente-systemes-mobilite-nouvelle-chaire>

concern the LTCI. To compensate for its side effects on laboratory life, an in-depth analysis in coordination with the human resources department is probably necessary.

The laboratory website has been integrated into the Télécom Paris website, it is now managed by the same webmaster as the school website. This allowed us to avoid a lot of redundancies and gave the laboratory visibility in communication about the school's scientific activity. With the creation of the scientific communication unit at IP Paris, there is a desire to redesign the websites of the various IP Paris laboratories which will probably lead us to detach the LTCI website from that of the school.

Recommendation C: *Le comité encourage l'unité à poursuivre dans sa dynamique de décloisonnement des équipes par la définition des axes transverses très pertinents en termes de thématiques scientifiques et d'organisation. Le comité recommande de définir des personnels pour assurer leur animation de façon suivie et pérenne, et éventuellement de les soutenir par des moyens dédiés (e.g. soutiens récurrents, bourses de thèse interéquipe).*

As said above, the laboratory tried to encourage and financially support the organization of cross-team seminars, but without going so far as to assign staff dedicated to this task. This is certainly what should be done in the next period.

Recommendation C: *L'accompagnement des doctorants et post-doctorants du laboratoire en vue du déménagement à Saclay doit être renforcée, en particulier en anticipant d'éventuelles difficultés pour les doctorants qui travaillent sur des plateformes qui seront rendues indisponibles momentanément. Il pourra être envisagé des séjours longs dans des laboratoires étrangers afin de valoriser au mieux la période transitoire.*

As mentioned above, the move of the platforms was well managed. No significant delay in the progress of PhD thesis and the work of post-doctoral students was observed.

1.7.2 Teams level recommendations

I – Communications and Electronic

C2S team

Recommendation A: *Les collaborations avec les équipes du département COMELEC mais aussi avec d'autres équipes comme S²A et RMS peuvent être une vraie opportunité pour élargir le champ scientifique couvert. Cela devrait permettre d'améliorer la visibilité de l'équipe au niveau international sur certains sujets mentionnés dans le projet à cinq ans.*

Indeed, we increased our collaboration with the other LTCI teams. Firstly, we co-supervised with O. Fercoq (S²A team) the thesis of Antoine Back, broadening our theme towards ML algorithms and optimization, which gives rise to an ECG classification with high accuracy classification and very low energy consumption. Secondly, a collaboration with A. Tchamkerten from the digital communication team (ComNum) has been carried out within project ADASENSE. This collaboration focused on reducing energy consumption for sparse communication IoT devices. We proposed a novel technique that reduces the energy consumption of wake-up receivers of IoT nodes by around 50%. This technique was patented and presented in detail in an IEEE Transactions journal. Currently, within the PEPR-future networks, C. Jabbour (C2S team) is planning joint work with P. Ciblat (S²A) and M. Coupechoux (RMS) on Energy Sobriety for Future Access Networks. The objectives of this collaboration are to study 6G use cases to evaluate its compatibility with greenhouse gas emissions reduction, to develop energy consumption models by analyzing electronic components in equipment, and to propose network sizing tools that maximize the QoS under the constraint of a certain greenhouse gas emission trajectory. In the future, we plan to reinforce our collaboration with S²A in the context of parameter selection for efficient classification.

Recommendation B: *L'accueil de chercheurs ou de professeurs étrangers pour des séjours longs est à encourager et à développer afin de renforcer les liens à l'international et consolider la visibilité internationale des travaux menés au sein de l'équipe.*

The team is proud to regularly welcome professors on sabbatical leave. Even though the last period was not favorable due to the pandemic, we welcomed Professor Oleg Vityaz from the National Technical University of Ukraine in 2022. In collaboration with Rayan Mina, Assistant Professor at the Electrical Department, ESIB-USJ, we carried out a complete overview of the existing state-of-the-art machine learning techniques used in analog circuit sizing and analyzed their effectiveness in achieving the desired goals. Hua Fan, a Professor of the University of Electronic Science and Technology of China and affiliated with Pavia University, will be hosted by the C2S team from 01/10/24 to 31/12/24. She will collaborate with C. Jabbour on the use of Artificial Intelligence for the design of mixed signal systems especially Digital to Analog Converters.

Recommendation C: *Les axes de recherche mentionnés sont tout à fait pertinents. Il faut veiller à ne pas se disperser et à travailler en parfaite intelligence avec les autres équipes du LTCI afin de pleinement tirer parti de toutes les compétences disponibles en interne et en externe.*

Our collaborations with the LTCI teams are detailed above. Moreover, we started a collaboration (still ongoing) with the CEA in line with our research activities on the linearization of PAs. During Joe Bachi's thesis, the CEA contributed with strong expertise on the design of PAs (from the device level to the module), as well as on the electrical and RF simulation and measurement. This was complementary to our contribution focusing on system-level modeling and signal processing specifically for digital predistortion. The collaboration continues now on investigating new design strategies to jointly optimize the amplifier module design and the digital predistortion processing (PEPR-FN). This is done specifically for newer power amplifier architectures such as LMBA. For the future, we are planning to collaborate with the SSH team on a key topic for electronic system design, that we started during this period: Circuits for AI and AI for circuit design.

ComNum team

Recommendation A: *Suite à la diminution des effectifs des permanents ces deux dernières années, on peut craindre une diminution du périmètre scientifique couvert par l'équipe ComNum et du rayonnement à l'international. Ce point a bien été identifié par les membres de l'équipe. L'équipe devrait pouvoir renforcer toujours plus sa visibilité à l'international par une implication dans de nouveaux projets du programme H2020.*

The team managed to maintain a high scientific productivity during the last five years. The members diversified their research portfolios. In addition to their traditional competencies, they now also work on reinforcement learning, theoretical aspects of machine learning, Markov decision processes, satellite communication, Quantum communication, and sensing. We believe that the team was able to maintain its good international reputation. This is underlined by the invitations obtained for sabbatical stays at leading international universities as well as the roles that the team members played in scientific evaluation committees (IEEE ITW TPC chair, AEs and lead guest editor for IEEE journals, IEEE award committees) for major international journals, conferences, and IEEE societies.

Recommendation B: *L'ouverture vers l'international doit se poursuivre. La tenue de séminaires réguliers est à encourager.*

Monthly internal seminars were organized by our PhD students, to present the progress of their research work. Unfortunately, the COVID pandemic also impacted our scientific seminars. Over the last two years, we could nevertheless host several national and international speakers on different topics spanning from cryptography over communication and information theory to machine learning.

Recommendation C: *Les perspectives scientifiques à cinq ans s’inscrivent principalement dans le cadre des réseaux 5G, voire 6G, et de l’IoT. Les travaux menés par l’équipe ComNum devraient notamment enrichir ces futurs systèmes et contribuer à nourrir les futures normalisations. L’implication dans de nouveaux projets européens devrait permettre d’augmenter cette influence sur les futurs choix normatifs.*

Our team has a strong focus on future cellular and IoT standards. We contribute to the package PC3, PC4, and PC9 of the national PEPR 5G initiative. The team also submitted proposals to various European calls (H2020, Horizon Europe): 3 ERC consolidator grants (1 accepted, 1 passed to the second round), 1 ERC proof of concept grant (seal of excellence), and participation in a project submitted to the European 2021 SNS 6G call.

Comment: *Par ailleurs, cultiver l’attractivité de l’équipe pour attirer de très bons étudiants capables d’adresser les sujets de thèse ambitieux proposés par l’équipe reste une préoccupation d’actualité.*

In collaboration with other institutes of IP Paris, the team has started the MICAS Masters program on the topic of communications, machine learning, and security. This Master’s program has attracted excellent students, and many are interested in pursuing a PhD in these areas. The team members teach also in related master’s programs (ROSP and Multimedia Networking), which also host excellent PhD candidates.

GTO team

Recommendation A: *Compte tenu du niveau exceptionnel des résultats de l’équipe (publications, rayonnement, contrats, . . .), le comité ne peut qu’encourager l’équipe à poursuivre cette dynamique.*

The GTO team remains dedicated to advancing optical communication systems, through collaborative work within the team and beyond.

Recommendation B: *Il semble important de mieux fédérer les travaux menés dans GTO avec une vie d’équipe plus structurée, par exemple grâce à des réunions régulières des cadres scientifiques (avec ou sans les doctorants)*

From 2013 to 2018, GTO indeed held monthly team meetings for the faculty members, postdocs, and doctoral students, during an important part of this period. Between 2018 and 2023, the meetings were initially irregular and online due to the Covid pandemic. After the pandemic, the monthly team meetings resumed. There is also a significant exchange by email, discussing life at school.

Recommendation C: *Le projet est excellent. Le seul risque est celui de la dispersion, compte tenu de la faible taille de l’équipe et du nombre important de thématiques traitées.*

We have addressed the comment on "dispersion" or lack of focus in our response to Comments 1 and 3. The scope of our work is photonics communications, with an emphasis on experimental research (covering physics, devices, algorithms, and network aspects). The team has recently consolidated its activities in this domain into four focal axes, each covered by 2–4 faculty members. The new organization helps us conduct our work more effectively.

Comment 1: *Il est difficile de faire mieux en termes d’implication et de production scientifique pour une équipe de cette taille. Le seul risque, avec un tel effectif, est celui de la dispersion. Avec six thématiques portées chacune par deux ou trois personnes (voire une seule pour la thématique 5), un essoufflement à terme de certains thèmes est possible. Enfin, on notera une forte activité autour de la conception et de la caractérisation de lasers à boîtes quantiques. Comme il n’y a pas de moyens technologiques à Télécom ParisTech, ce thème doit être mené en collaboration avec d’autres laboratoires pour s’assurer de la pérennité de ces collaborations.*

The team has consolidated the six research axes presented in the 2018 report into four axes in the current report. Two of the areas were closely related to semiconductor physics and optoelectronics, and have now been merged into one area. Instead, there is now a distinct area on quantum technologies. Each axis currently has 2–4 people involved. The new organization should help better conduct our research in our focal areas of activity.

Regarding the activities on quantum dot devices, the team has cultivated strong and exceptionally fruitful research partnerships within the worldwide innovation ecosystem. Notably, we have collaborated intensively with Professors L. F. Lester at the University of New Mexico, C. W. Wong at UC Los Angeles, and J. E. Bowers at UC Santa Barbara. The experimental work is performed partly through such collaborations.

Comment 2: *Compte tenu de la très forte activité de l'équipe, les points à améliorer sont minimes. On pourrait néanmoins souhaiter une plus forte interaction avec les autres laboratoires académiques parisiens. L'optique est un thème fort à Paris (en particulier du côté de l'Université de Paris-Saclay) et l'équipe pourrait aisément participer à cette dynamique de site. L'implication de l'équipe vis-à-vis de la vulgarisation de la recherche est plus modeste, mais le comité note néanmoins des interventions lors de la fête de la science ou dans des lycées.*

The GTO team has indeed forged several collaborations in the Saclay area in the past years. Nicolas Fabre, who joined the GTO team recently, is working with Nadia Belabas of C2N on a joint project on quantum information processing and co-supervises a postdoc with her there. Nicolas is also currently working with the researchers from the Sorbonne Université and Orange Innovation Lab on building a regional QKD network.

Frederic Grillot has also established collaborations with C2N, Nadia Belabas, Adel Bousseskou, and Raffaele Colombelli. Renaud Gabet collaborates with Delphine Morini at C2N. Several members of the team collaborate with the QURIOSITY team, and through that, with the Quantum Saclay Center, a research center of the Institut Polytechnique de Paris and Université Paris-Saclay that aims to be a leading international ecosystem on quantum technologies.

Comment 3: *Vu la qualité des résultats obtenus et la faible taille de l'équipe, il est important que GTO puisse recruter. Dans ce cas, l'équipe atteindra une taille qui nécessitera la mise en place d'une vraie structure, avec des réunions régulières et ainsi mieux fédérer les travaux menés par ses permanents.*

The GTO team has recruited a new Assistant Professor in 2023, Nicolas Fabre, who works in quantum physics and technologies. In 2024, the team is also in search of a faculty member broadly in photonics. The GTO has an updated structure described in Section 5.3 (see also our response to Comment 1), as well as regular monthly team meetings for the faculty members, postdocs, and doctoral students.

Comment 4: *Le projet aurait mérité d'être un peu plus développé sur certains points structurels, en particulier liés au déménagement vers le plateau de Saclay. Par ailleurs, ce projet est vaste et la taille relativement faible de l'équipe ne permettra peut-être pas de traiter complètement tous ces domaines sans de nouveaux recrutements.*

As indicated in our response to Comment 1–3, the team was indeed restructured in the past years, in response to the advances in photonics (particularly, the substantial interest in quantum technologies), the recent and ongoing recruitments, the move to the plateau Saclay, and other activities at the LTCl. There are now fewer focal research areas, with more people in each area.

LabSoC team

Recommendation A: *Les deux recommandations importantes concernent d'une part la politique de publication qui doit être recentrée sur des journaux et conférences reconnus, d'autre part la durée des thèses, qui doit être réduite.*

LabSoC has published in top conferences in its field (e.g., Models and DATE), and has published several articles in well-known journals (e.g., ACM Transactions on Embedded Computing Systems, Software and Systems Modeling, 2023, Springer Nature). Concerning the PhD duration, we have paid particular attention to this point, especially when the PhD subject is linked to previous work in the team. For the PhD projects started on new research topics, connected to our main expertise (model and verification of embedded systems), the duration of the PhD may take a bit more time.

Recommendation B: *Pas de remarque particulière.*

Recommendation C: *Le comité encourage fortement l'équipe à réfléchir à des partenariats académiques pour réaliser le projet de recherche, en collaborant avec les équipes du LTCI qui sont sur des thématiques proches (notamment SSH et ACES). Le comité recommande également de travailler dans un partenariat étroit avec des acteurs de la recherche sur le site de Sophia, à Eurecom, au LEAT (Laboratoire d'Électronique, Antennes et Télécommunications), ou encore à Inria par exemple.*

Concerning the interaction with SSH, we set up several Ph.Ds and post-doctorates in collaboration with the SSH team. Currently, we have 3 ongoing PhD with SSH. 3 new PhD students and 1 postdoc are expected to start in collaboration with SSH in 2024. They will be recruited as part of joint projects (e.g., PERP 5G and PERP Security, ...).

For better interaction with the local institutions of Sophia-Antipolis, we set up new activities, both on the research and teaching sides. Concerning research, a PhD in collaboration with Inria Sophia-Antipolis was hired and successfully defended in 2023. A CIFRE PhD was started with Renault Software labs at Sophia-Antipolis and also defended in 2023. We also have a continuous stream of publications co-written with Inria Sophia-Antipolis. Moreover, each year we now organize the PhOwn⁹ security competition in cooperation with the University of Nice and the LEAT laboratory, both located on our campus (200 participants in 2023). In 2023, we set up a BPI project with Prove&Run (Sophia-Antipolis), and its acceptance is still pending (the first phase was successful). Concerning our teaching activities, we are involved in lectures in our research domain in Polytech'Nice. ARM, Cudasip and Texplained, 3 companies of the Sophia-Antipolis ecosystem are involved in our lectures and laboratory work. Finally, many of our students do their internships in Sophia-Antipolis, we therefore have continuous interactions with many companies, including NXP, Alten, and Arteris.

RFM² team

Recommendation A: *Les résultats sont excellents, le comité ne peut donc qu'encourager l'équipe à poursuivre dans la même voie.*

Recommendation B: *L'équipe semble avoir mis en place les structures nécessaires à une véritable vie d'équipe et à des collaborations avec les autres équipes. Il est important que cette équipe de haut niveau très orientée « hardware » ne soit pas isolée et donc défavorisée par rapport à un environnement « numérique » plus conséquent au sein de LTCI.*

The team is not isolated today and has benefited from the support of the LTCI with the arrival of new researchers. The contribution of these new researchers has enabled the creation of a new theme and the strengthening of an existing one. In circuit design, the recruitment of K. Niotaki launched a new theme on energy harvesting and far-field wireless energy transfer. The nonlinear circuit activity was strengthened by the arrival of R. Mohellebi, also involved in the C2S team, on the characterization of non-linear millimeter-wave power components. The growing activity of the C2M chair (Characterization, Modeling, and Control of Exposures) involves collaborations with other departments such as IDS and Infres. As an example, in the Embryorad project granted by ANSES, numerical fetus models are developed by IDS to assess the exposure induced by a mobile

⁹<https://ph0wn.org/>

phone model developed by us and held by a numerical model of the mother.

Recommendation C: *Les perspectives telles qu'elles sont décrites ne doivent pas poser de problème majeur. L'équipe a le potentiel pour explorer des thématiques plus audacieuses encore.*

SSH team

Recommendation A: *Le point de vigilance concerne principalement l'encouragement des jeunes collègues à publier dans les journaux.*

During the period in question, attention was given to young colleagues to prioritize publications in journals, which notably led two of them (Laurent Sauvage and Ulrich Kuhne) to engage in preparing their *Habilitation à diriger des Recherches* (HdR).

Recommendation B: *Après le déménagement sur le plateau de Saclay, le comité ne peut qu'encourager l'équipe à travailler en collaboration avec les acteurs de la recherche en présence, et de participer à l'organisation de la vie scientifique sur le site. Il est recommandé également à l'équipe d'encourager les collègues moins visibles sur les publications dans les revues scientifiques reconnues à le faire.*

The team has actively contributed to advancing scientific initiatives in collaboration with stakeholders from the Plateau de Saclay, notably the Institut Polytechnique de Paris, Université Paris Saclay and the CEA. These efforts have encompassed both training initiatives, such as the IP Paris E3A master program and the SETI and ICS M2 programs in collaboration with both universities and research initiatives, such as participation in prize committees for the entire doctoral community (Plateau de Saclay Doctoral Awards).

Recommendation C: *Le projet est cohérent avec les forces et compétences de l'équipe et la politique du laboratoire. Le comité invite l'équipe à tisser des liens avec d'autres équipes du LTCI et avec les acteurs présents sur le plateau de Saclay.*

The actions that the team has taken to strengthen or create new links with other teams within the LTCI or the *Plateau de Saclay* have resulted in co-supervision of theses, joint publications (see [999, 998]), and joint responses to project calls (SODA, SPARTA, etc.).

Some examples of PhD supervision are Dorian Bourgeoisat (SSH-ACES), Maxime Ayrault (SSH-ACES), Nicolas Schlegel (SSH-C2S), Evelyn de Oliveira Lima (SSH-C2S), Dorian Gaillard (SSH-MM), Xuecan Yang (SSH-S²A), Léopold Clément (SSH-LabSoc).

II – Computer Science and Networks

ACES team

Recommendation A: *L'activité de rayonnement et d'activités contractuelles dénote un excellent dynamisme. L'équipe doit néanmoins mettre en place une stratégie de publication de façon à augmenter la qualité de la production scientifique.*

The scientific output has increased, with more than 60 journal articles and more than 145 articles in conference proceedings.

Recommendation B: *Le comité encourage l'équipe à continuer de développer ses collaborations avec les acteurs du site, une fois le déménagement à Saclay effectué. L'équipe doit inciter les MCF à passer leur HDR.*

The ACES team, in collaboration with the LIX Computer Science Laboratory of École Polytechnique and the U2IS team at ENSTA Paris, has launched the joint initiative $\Sigma K \Phi$ focusing on cyber-physical systems. This initiative has led to joint seminars, the set up of a research project, and the co-supervision of doctoral theses.

During the specified period, one associate professor has completed his HDR (Habilitation à Diriger des Recherches). Two others are currently registered for a defense before the end of the 2023-2024 academic year, and one other is expected to defend before the end of 2024.

Recommendation C: *Le projet proposé est globalement cohérent avec les compétences et le futur déménagement. Le comité encourage l'équipe à anticiper les futurs départs afin de le mener à bien.*

The scheduled departures have been anticipated and the team size has remained stable and has retained the same number of professors. However, the situation continues to be monitored, as one full professor will retire at the end of the year.

C2 team

The C2 team was created after the previous assessment. Below we take up the recommendations of the former MC2 and CCN teams, some of whose members now make up the C2 team. Next, we respond to a few comments that we believe are important to bring to the attention of the team's evaluation jury.

Recommendation A: CCN – *Le comité recommande à l'équipe de mieux sélectionner ses participations aux conférences. Elle a le potentiel pour accroître la qualité de celles-ci.* MC2 – *L'équipe se définit comme principalement mathématicienne, mais les questions qu'elle adresse sont fréquemment motivées par l'informatique, et les résultats qu'elle obtient y trouvent régulièrement des applications. Le comité suggère à l'équipe de tenter de concrétiser ces applications au travers de collaborations avec le reste du LTCl.*

Recommendation B: CCN – *Le comité encourage l'équipe à développer ses collaborations avec les acteurs du site, une fois le déménagement à Saclay effectué. Le comité encourage également l'équipe à organiser des réunions d'équipe et à organiser des séminaires. Une réflexion peut être menée également concernant l'évolution prévisible de la pyramide des âges et sa déclinaison possible en une stratégie d'évolution et/ou de recrutements à envisager.* MC2 – *Les membres de l'équipe collaborent déjà les uns avec les autres. Le comité invite l'équipe à mettre en place un séminaire régulier, afin de ponctuer la vie de l'équipe, mais aussi pour promouvoir le thème informatique mathématiques au sein du LTCl et des étudiants de Télécom ParisTech. De la même manière, le comité recommande de prendre à leur charge, l'animation scientifique du thème transversal "modélisation mathématique" souhaité par le laboratoire. À titre d'exemple, le comité pense que l'invitation sur un rythme bimensuel d'un orateur sur une thématique théorique d'intérêt général (codage, cryptographie, théorie des graphes, ...), permettra de jeter des ponts entre les équipes du LTCl.*

Recommendation C: CCN – *Le projet est globalement cohérent, mais il ne semble pas évident de scinder les projets 4 et 5 sur les « blockchains ». Le projet 2 sur les larges réseaux est fédérateur, projet dont il faudra mieux expliciter la mise en oeuvre.* MC2 – *L'équipe devra assumer pleinement son rôle de promotion de l'informatique théorique. De ce point de vue la création de NewUni, avec notamment la proximité de l'équipe Grace du LIX, constitue une opportunité à ne pas manquer.*

Comment 1: *Le comité invite l'équipe à mettre en place un séminaire régulier*

We have been organizing a regular seminar since 2020, featuring over 20 speakers, including renowned individuals such as Yvo Desmedt (Member of the Belgium Academy of Science), Damien Stehlé, Liqun Chen, and others.

Comment 2: *Le comité encourage l'équipe à développer ses collaborations avec les acteurs du site, une fois le déménagement à Saclay effectué.*

we collaborate with the Grace Team in joint ANR projects and co-supervision of PhD students. With the arrival of Victor Dyseryn, who works on code-based cryptography, we will strengthen

the collaboration in post-quantum cryptography. Additionally, we collaborate with other teams in Saclay such as the ENS Paris-Saclay (particularly with Caroline Fontaine) and with the CEA (Renaud Sirdey’s team) in the PEPR SecureCompute.

Comment 3: *Le comité recommande à l’équipe de mieux sélectionner ses participations aux conférences*

C2 is now among the best teams in France in terms of publications at flagship conferences in cryptography and privacy, namely Crypto (A*), Eurocrypt (A*), Asiacrypt (A), PoPETs (A).

DIG team

Recommendation A: *L’équipe est encouragée à continuer à publier au meilleur niveau ses résultats scientifiques et poursuivre ses partenariats académiques et industriels. Ceux-ci pourraient s’inscrire dans des projets de plus grande ampleur (projet Européens, ERC) pour accroître encore la visibilité des résultats.*

The DIG team has maintained a high level of publications. New academic and industrial collaborations have been initiated, through the ANR chair NoRDF and ANR projects, the joint lab TALia and CIFRE contracts. The team has a strong link with the University of Waikato (New Zealand) where Prof. Albert Bifet has a permanent position. The team applied for a Horizon Europe project in 2023 but this was rejected. Despite this, the research activity of the DIG team is extremely visible, not only through the publications but also thanks to the datasets (the YAGO knowledge base) and the software developed and maintained by the team.

Recommendation B: *Les travaux croisés entre les différents sous-thèmes de l’équipe doivent être poursuivis. Des rapprochements avec l’équipe S²A, notamment autour des axes transversaux liés à l’IoT et à la Science des Données, sont à envisager avec une identité propre à chaque équipe mieux définie. L’implication de l’équipe dans les actions structurantes du laboratoire, comme les « topics » et axes transversaux, devrait être renforcée. Les thématiques couvertes par l’équipe sont au coeur de plusieurs de ces axes.*

Existing collaborations within the team have been continued and new ones have emerged, especially since the recent hiring of Mehswish Alam and Nils Holzenberger. In terms of positioning, the focus of the DIG team is clearly on the computational aspects of data science and artificial intelligence, from the most theoretical aspects (complexity analysis, performance guarantees, languages, logics) to the more practical aspects (online machine learning, neuro-symbolic methods, explainability, datasets, open software). Thus the DIG team is very active in the axis *Data Science and Artificial Intelligence* of the LTCl.

Recommendation C: *Les collaborations intra-équipe mais aussi avec une partie de l’équipe S²A devraient être renforcées pour permettre la réalisation du projet.*

New collaborations have been initiated, both inside the team, most notably on the evolution of the knowledge base YAGO, and with other teams of the LTCl, particularly on the topic of NLP with the S²A team.

DIVA team

Recommendation A: *Afin d’amplifier les relations internationales, l’équipe DIVA pourrait inviter de façon plus régulière des professeurs étrangers.*

The team hosted Harpreet Sareen (Parsons, The NEW School) as a visiting professor and several week-long visits from Clemens Klokmoose of Aarhus University. Additionally, PhD student exchanges were hastily aborted as a result of the pandemic.

Recommendation A: *Compte tenu des développements réalisés dans le cadre des projets de recherche (démonstrateurs technologiques en particulier), une meilleure valorisation des travaux par des brevets et/ou des transferts de technologies pourrait être faite. Les relations industrielles de l'équipe pourraient être développées en appui des différents outils à disposition de l'équipe dans son environnement proche (relations industrielles de Télécom ParisTech, projet d'intégration sur le plateau de Saclay, institut Carnot Télécom & Société Numérique).*

The DIVA team generally favors open diffusion of its results through open publications and open-source software. Nonetheless, the team has one patent in the period, relating to MobiLimb interfaces [<https://patents.google.com/patent/FR3086195B1/en>] and one in progress with EDF. This work has also led to DIY (Do-It-Yourself) video tutorials to facilitate the adoption of its techniques. The team has hosted a CIFRE thesis with EDF (Ming Ming Qiu) and is developing collaborations with the independent research lab Ink & Switch through the Webstrates project.

Recommendation B: *L'organisation de séminaires scientifiques avec l'équipe ComNum (en liaison avec ce qui se fait déjà avec l'I3) permettrait des échanges au niveau de l'ensemble des personnels de l'équipe. L'implication des co-encadrants de l'équipe ComNum et/ou des doctorants concernés dans les séminaires de l'équipe DIVA mériterait d'être plus importante.*

The team has instead expanded collaborations with the I3 laboratory following the development of the SocialTouch and SecondSkin research directions (co-supervised PhDs with Stéphane Safin and Françoise Détienne), with the Equipex Continuum project (Stéphane Safin, Samuel Huron, and Michael Baker), and also pursuing the explainable AI research direction (with Winston Maxwell and David Bounie). The SecondSkin project involves collaborations with the LIG in Grenoble (Céline Coutrix) and with physicists at the PMMH (Benoit Roman). Additionally, the team has leveraged the departure of J. Gugenheimer to maintain regular collaborations with TU Darmstadt. The team also has continued its collaboration with LRI (now LISN) through continued co-supervision of PhD students (e.g., Jiali Liu, Gaëlle Clavelin, etc.).

Recommendation C: *Les relations existantes avec le LRI et I3 sont structurantes et doivent être confortées au cours des cinq prochaines années pour mener à bien les recherches envisagées. Afin que l'équipe DIVA maîtrise mieux ses axes de recherche, le nombre d'HDR de l'équipe devrait être augmenté.*

The team has added a new HDR (E. Lecolinet) and a reduced teaching load has been granted to J. Eagan to facilitate the obtention of his HDR. Associate member Samuel Huron (I3) is also currently working on his HDR. Nonetheless, with the departure of G. Bailly, this remains a point of vigilance.

QURIOSITY team

The QURIOSITY team is a joint team with Inria created at the beginning of 2023. It succeeds the IQA team, whose former members are now part of the QURIOSITY team. Below we list the recommendations made to the IQA team to which the QURIOSITY team responds.

Recommendation A: *Le comité encourage l'équipe à continuer l'excellence de sa production scientifique. Pour l'avenir, le comité rappelle le risque qu'il y aurait à vouloir recentrer et cantonner cette équipe aux aspects purement communications quantiques, dans leurs dimensions expérimentales et applicatives. En effet, soulignons que c'est précisément la capacité d'exploration d'idées nouvelles, nées d'un va-et-vient avec les fondements de l'informatique quantique qui a fait la richesse, et la spécificité de positionnement scientifique, de cette équipe.*

The QURIOSITY team has been able to maintain and probably develop the excellence of its scientific production over the period. Thematically, the former IQA team has shifted its activity towards research questions that are more intensive in theory (quantum information theory,

cryptography and complexity), while maintaining its strong activity in experimental quantum communications, with key partnerships with the GTO team at Télécom Paris, C2N and with ENS Ulm. This positioning, together with the dynamism of the team activity, notably its participation in the Quantum Technology Flagship European project CIVIQ, but also the participation of Romain Alléaume to structure and grow quantum research activity at IP Paris have been pivotal to defining and creating the QURIOSITY team, and to make 4 several strategic hirings in 3 years, that have significantly expanded the team breadth of competencies as well as our research thematics.

Recommendation B: *Le comité n'a pas de recommandation à faire.*

Despite the absence of recommendation, we would like to emphasize that the transition from IQA to QURIOSITY and the rapid development of the team since then, has also consisted of structuring its activity around regular (at least weekly) group meetings, weekly seminars with external or internal speakers open in particular to PhD students, as well as mentoring of Quantum Engineering students (4-months research projects PRIM), offering overall an active scientific environment and promoting the involvement and progress of early-stage researchers.

Recommendation C: *Le projet est exceptionnel sur les aspects communications quantiques. L'équipe est encouragée à poursuivre sur cette voie. Les aspects systèmes complexes, informatique quantique et simulation sont eux à reconstruire. Le comité recommande à l'équipe de ne pas abandonner ce terrain ; et de faire valoir la perte de la moitié de ses membres permanents pour envisager de nouveaux recrutements sur les fondements de l'informatique quantique, afin de pouvoir effectivement porter ces thèmes. C'est d'autant plus crucial dans la perspective du déménagement à Saclay, où l'équipe devra-t-être en mesure de faire valoir ses spécificités, vis-à-vis d'une activité expérimentale déjà intense en optique quantique. Le comité incite l'équipe à peser pour transposer, et généraliser au plateau de Saclay, son excellente initiative de création d'un parcours niveau Master 2 en Quantum Engineering.*

As mentioned above, the creation and development of QURIOSITY have led to greatly expanding the thematic horizon of the team, while maintaining its coherence. QURIOSITY research program is now centered on theoretical challenges in quantum information processing, related notably to mathematical and computer science questions. The team is also keeping strong activity and collaborations in quantum engineering, in particular on quantum communications. The team has moreover pushed forward the development of the Quantum Engineering master (M2) program, doubling the number of students per year. The perspective is now to unite forces between strategic partners on the Saclay plateau, to launch a dedicated M2 in Quantum, Mathematics, and Computer Science.

RMS team

Recommendation A: *La production scientifique doit être poursuivie à ce niveau d'excellence et renforcée sur la sélectivité des supports de communications en conférence. L'investissement dans le développement de plateformes et les partenariats collaboratifs doivent être maintenus et éventuellement mutualisés au niveau de l'environnement du plateau de Saclay.*

Both the selectivity of conferences and the location of these conferences will be taken into account to limit the carbon impact of the team's missions.

We have now several research platforms that are open to various institutions in France and Europe (see our Portfolio). Most prominently, there is the platform 5gmMTC in collaboration with the Versailles Saint Quentin University and some medium-sized companies of the Ile-de-France region. We are a member of the French node of the SLICES-FR project (with CNRS and Inria).

Recommendation B: *La vie de l'équipe doit être renforcée en particulier pour permettre de dégager des synergies plus nombreuses entre les membres de l'équipe.*

Our scientific topics can be divided into three parts: modeling and algorithms; architectures and protocols; platforms, and industrial valorization. As we are interested in the analysis of global systems, we must, in essence, collaborate to define the telecommunication systems of the future. During the past five years, each of us had at least one, and often several, publications with other members of the teams. There is a true convergence of interest between IoT, core and radio access networks which we emphasize in our joint communications.

Recommendation C: *Même si le projet scientifique est globalement très bon, l'équipe doit veiller à ne pas trop se disperser. La plateforme SILECS présente de réelles opportunités que l'équipe devrait davantage exploiter. Elle pourrait donner lieu à de la mutualisation à une large échelle en particulier en termes de personnel, ce qui permettrait le maintien de nouvelles plateformes expérimentales par exemple liées à la 5G.*

We recruited a team of 3 permanent engineers devoted to the software development of the SDR platforms.

III – Image, Data and Signal

IMAGES team

Recommendation A: *L'équipe s'est dotée d'une plateforme d'intégration logicielle qui devra montrer son efficacité et sa pérennité. L'équipe devra assumer la perte à venir d'une compétence forte en imagerie physique en renforçant ses compétences en modélisation mathématique pour l'imagerie physique.*

There is no "software integration platform" in the team and we have no idea what is referred to here.

Concerning the retirement of Jean-Marie Nicolas, and the competencies in physical imaging, the team has made a recruitment in 2020 that we consider as very successful. Christophe Kervazo was the first choice of the team after the recruitment procedure, has noticeably increased our competencies scope through source separation and hyper-spectral imaging, and is perfectly in line with the importance of the team of both mathematical modeling and acquisition systems.

Recommendation B: *Une implication renforcée dans l'animation des différents axes transverses du laboratoire devra permettre d'amplifier le sentiment d'appartenance à une Unité de recherche du plateau de Saclay.*

The transversal axes of the laboratory have been redefined to be in line with the transversal axes of the IDIA department of the Institut Polytechnique de Paris. In these axes, the team is particularly concerned with Axis 4 (Robotics, visual and audio computing, and interaction) and Axis 6 (Data science and artificial intelligence). The team was heavily involved in the animation of Axis 4 (co-responsibility for the workshops organized on this theme and the organization of half-day scientific seminars) which brings together teams from the LIX laboratories (Ecole Polytechnique), SAMOVAR (Télécom SudParis) and U2IS (ENSTA).

Recommendation C: *Le projet scientifique se situe dans la continuité de l'expertise reconnue de l'équipe, qui devra hiérarchiser ses priorités et identifier les verrous scientifiques que l'équipe veut et pourra traiter dans les cinq années qui viennent. L'équipe devra ainsi veiller à poursuivre son activité en modélisation mathématique des images tout en conservant son expertise historique en imagerie médicale et télédétection.*

The team has strengthened its activity in mathematical modeling, in particular with the recruitments on this theme of Loïc Le Folgoc (2022) and Arthur Leclaire (2023), besides Christophe Kervazo already mentioned. These recruitments, our first choice after the recruitment procedure, are considered by the team as highly successful and broadly enlarge our competencies in optimization, machine learning, stochastic modeling, optimal transport, and plug-and-play methods among others. The team has also largely developed its skills in statistical learning internally. It has also retained its historical expertise on the theme of medical imaging (a return from CNR, Elsa Angelini, and the recruitment of Loïc Le Folgoc), image restoration (Arthur Leclaire), and remote sensing (Christophe Kervazo).

MM team

Recommendation A: *Le spectre d'activité de l'équipe a été très large durant ces dernières années allant de la participation à des comités scientifiques internationaux à l'organisation de conférences prestigieuses, tout en maintenant une activité de recherche académique soutenue ainsi qu'une forte implication dans le domaine de la normalisation et du transfert technologique. Il est clair que la recommandation principale que l'on peut donner est de continuer dans cette voie d'excellence. Par ailleurs, il est important que l'équipe soit renforcée dans les prochaines années. Cela passe probablement par la mise en place d'une interaction plus forte entre les deux axes restants, qui semblent conduire des recherches de façon indépendante sur un domaine relativement connexe (les*

services multimédia). Il serait aussi intéressant de nouer des liens avec des équipes telles que ComNum ou encore IMAGES.

Une option alternative serait d'envisager une réduction du périmètre d'activités et un recentrage sur certains axes prioritaires. Par ailleurs, l'équipe devrait à l'avenir pouvoir conforter sa visibilité à l'international en se positionnant sur un projet d'ERC.

Following the previous recommendation, our goal over the past five years has been to preserve the team's wide-ranging activities, including its active participation in international scientific committees and its commitment to conducting strong academic research. Additionally, we have significantly been engaged in standardization and technology transfer actions.

In response to the need for strengthening the team, notably increased by the departure of Pr. Marco Cagnazzo, we have successfully hired three associate professors since 2018. Following this departure, the team was strategically reorganized around two main axes: "Transmission of Multimedia data" and "Efficient deep learning for multimodal data". This structure has been effective, as several researchers contribute to both axes, ensuring a cohesive and well-integrated team dynamic. In parallel to these changes, we have started several collaborations with the COMELEC department (4 PhDs in co-supervision) and with the IMAGES team (leading to an ICLR publication).

The newly recruited young researchers have actively pursued significant funding opportunities, with all of them submitting proposals to the ANR Young Researchers (JCJC) program. Notably, Stéphane Lathuilière achieved success in this endeavor with his *Odace* project.

Recommendation B: *L'équipe de recherche MM s'organise aujourd'hui autour de deux grands axes de recherche. Les interactions entre ces deux axes ne sont cependant pas claires, alors que certaines de leurs thématiques sont complémentaires et adressent les mêmes services Multimédia. Un décloisonnement de ces axes de recherches au sein de l'équipe serait donc un plus appréciable, ainsi que l'organisation de séminaires internes qui est aussi une action à encourager.*

Enfin, il faut noter que grâce à sa visibilité internationale, son dynamisme, ainsi que grâce à la reconnaissance de ses travaux de recherche, l'équipe MM est indéniablement très attractive auprès des bons étudiants, et très active au niveau de la formation par la recherche, assurant une production scientifique de qualité. Il faut continuer dans ce sens dans les années à venir.

Please refer to the previous comment for details on the research axes. Concerning the elimination of internal partitions, we have adhered to the HCERES guidelines and now host weekly internal seminars aimed at fostering collaboration. These seminars are topic-dependent and open to researchers from other teams to enhance interdisciplinary interaction.

Recommendation C: *Le projet à cinq ans est ambitieux à l'image du travail que l'équipe a réalisé ces dernières années. Il s'intègre parfaitement dans la dynamique de l'équipe ainsi que dans les perspectives du laboratoire LTCI. Les domaines de recherche traités par l'équipe MM et plus particulièrement ceux de l'axe distribution interactive de services et orchestration, sont cependant très guidés par les besoins industriels. Il faut faire attention dans ce contexte à maintenir une recherche académique de haut niveau. La faisabilité du projet est fragilisée, suite au départ de plusieurs de ses membres. Un regroupement des forces au sein de l'équipe serait à considérer, notamment par un décloisonnement de ses axes de recherche.*

Regarding the scientific project, in light of the numerous departures and considering the backgrounds of the recruits, along with the rapid advancement of deep learning in multimedia processing, we have adapted the team's objectives and organization accordingly. Our focus has shifted more towards developing deep learning learning methodologies, especially for multimedia and visual data processing. Despite these changes, our commitment to maintaining high academic research standards remains. We continue to foster industrial partnerships with prominent companies like Meta, Netflix, Atos, Zodiac, and Orange, ensuring that our academic pursuits are complemented by practical, industry-relevant collaborations.

S²A team

Recommendation A: *L'équipe S²A est encouragée à maintenir l'excellence de sa production scientifique et son engagement dans des partenariats industriels qu'elle réalise depuis de nombreuses années déjà. Pour ce faire, l'équipe devra assumer un certain repositionnement scientifique consécutif à de nombreux départs de cadres scientifiques historiques qu'elle a connus sur la période. Ce renouvellement s'accompagne également d'une possible menace quant à sa capacité à maintenir une formation de nombreux doctorants et de très bons niveaux. Pour faire face à ce risque, l'équipe doit garantir une bonne intégration de ses nouveaux membres les plus jeunes, et les accompagner rapidement vers leur autonomie scientifique.*

The S²A team has been able to maintain a high level of activity and to keep the excellence of its production in spite of a huge turnover over these last five years. With the constant renewal of the team's workforce, accompanied by a certain rejuvenation, the importance of certain scientific themes has naturally declined over the period (*e.g.* Monte-Carlo methods, analysis of stochastic processes), but that of other emerging subjects has grown rapidly (*e.g.* computational statistics, natural language processing, optimization). The strategy of S²A that consists of integrating recruits by offering them the opportunity to participate in collaborative projects led by the pillars of the team has been successful. The number of PhD students and post-docs has been stable or even on the rise over the period.

Recommendation B: *Le caractère fortement méthodologique d'une partie de l'activité scientifique de l'équipe justifierait le développement de collaborations plus étroites avec les autres équipes du département IDS, voire avec des équipes d'autres départements (par exemple l'équipe « Data, Intelligence and Graphs » du département « Networks and Computer Science »). Ces collaborations pourraient notamment s'inscrire dans la poursuite des objectifs scientifiques fixés par les axes interdisciplinaires soutenus par l'unité.*

La mise en commun de thèmes transversaux au sein de l'équipe et partagés avec le département IDS doit s'accompagner d'une gouvernance consolidée permettant la mise en oeuvre d'une politique scientifique propre à l'équipe, assurant une bonne gestion des moyens et contribuant à son identité. Pour démontrer la vitalité de l'équipe par sa participation à des cycles de séminaires, et pour assurer une plus grande diffusion des produits de la recherche en termes de publications, logiciels, et transferts, l'équipe S²A est invitée à enrichir et mettre à jour régulièrement les pages web qui lui sont dédiées sur le site de l'unité. Par ailleurs, sur la thématique de l'IoT envisagée comme nouveau champ applicatif investi par l'équipe, une collaboration plus étroite avec l'équipe DIG autour de l'activité "machine learning for data streams" serait pertinente.

Indeed, the methodological skills developed by the S²A team bridge many domains (*e.g.* AI for embedded systems, regulation of AI, algorithms for anomaly detection) and can be beneficial to many other teams within Télécom Paris. Over the period 2018-2023, S²A has intensely collaborated with various teams of the COMELEC, INFRES and SES departments, in the form of co-supervision of PhD theses in particular, providing skills in online and decentralized optimization or on the treatment of textual/structured/multimodal data for instance. The team has also actively participated in the building of the joint lab Talia hosted by the INFRES department and that of the initiative Operational AI and Ethics hosted by SES department.

Recommendation C: *Le projet de l'équipe s'inscrit dans un écosystème et contexte scientifique favorables au développement de ses activités, s'appuyant sur des compétences fortes en science des données, apprentissage automatique et intelligence artificielle. L'équipe devra veiller à dégager des priorités parmi les sollicitations qu'elle sera amenée à rencontrer. Plus généralement, dans ce contexte, il conviendra de définir des axes de recherche prioritaires, en accord avec la poursuite d'objectifs scientifiques clairement énoncés.*

Because the S²A team had defined its scientific perimeter and organization to perform well regarding the international standards, the main oral recommendation formulated by the previous

HCERES committee consisted of drawing its attention to the numerous opportunities offered by its new environment, on the Saclay campus. The team has considered this recommendation very seriously. Regarding teaching, the team massively participates in Master programs (e.g. Master Data Science of IP Paris, MVA at ENS Paris Saclay), and is strongly involved in the 5-year PhD track program of IP Paris, welcoming regularly promising (international) students. With no dispersal, the senior members of the team take part in most structures dedicated to the organization of scientific life, at IP Paris, *e.g.* IDIA and Maths departments, PhD grant committees, the academic board of IP Paris, the interdisciplinary center Hi! PARIS and beyond, *e.g.* the EDMH doctoral school, the labex DigiCosme, LMH, the FMJH. Scientifically, the team has reinforced its unique positioning within the local ecosystem over the period, characterized by well-recognized expertise in statistical/audio signal processing, social computing, and methodological machine-learning, which permits it to participate in upstream research projects while staying close to certain crucial applications (*e.g.* affective computing, machine-listening).

Chapter 2

Portfolio introduction

The laboratory portfolio is presented below for each team, ordered by department. It is made up of various elements: publications in leading journals and conferences, remarkable technology transfer actions, widely used free software, major contributions to successful standardization processes on technologies widely used today, as well as important alliances and collaborations with socio-economic actors on strategic research subjects. The whole reflects very well the profile of the laboratory and its scientific positioning.

2.1 Communications and Electronic

2.1.1 C2S Team

- Journal paper. **A novel approach for Doherty PA design using a compact L-C combiner** [83].

This paper presents a new method for analyzing and designing Doherty Power Amplifiers (DPAs) using a compact L-C combiner. The approach addresses a common efficiency issue in DPA design. The power amplifier module demonstrates improved minimum efficiency compared to previous LTE DPAs using L-C combiners (approx. 4%).

- Journal paper. **Power-aware feature selection for optimized analog-to-feature converter** [729].

This paper presents a new acquisition method for smart sensors called Analog-to-Feature Conversion. It is based on Non-Uniform Wavelet Sampling and aims at only extracting useful features for a specific task. A ML model then uses the extracted features to perform the task. The proposed solution was evaluated for ECG arrhythmia detection and showed an energy consumption divided by 15 compared to the classical solution of ECG acquisition.

- Book. **Digitally enhanced mixed signal systems** [89].

This book presents improvement techniques for current and future circuit and system design. It discusses how digital enhancement can address key challenges relevant to analog components in terms of shrinking CMOS technology, increasing user demand for higher flexibility and data traffic in communications networks, and the drive to reduce power consumption.

- Journal paper. **Wide frequency characterization of intra-body communication for leadless pacemakers** [92].

This paper presents a new in-depth IBC channel characterization involving computational modeling, in-vitro and in-vivo experiments. This successful work constitutes a keystone and a valuable reference for future developments.

2.1.2 ComNum Team

- Conference paper. **Age of Information Aware Cache Updating with File-and Age-Dependent Update Durations** [120].

Prestoring popular contents in cache memories close to end users has become a popular tool to reduce congestion and latency in communication networks. In this paper, an update policy is designed that minimizes the average Age of Information over files with respect to a given popularity distribution.

- Journal paper. **Local decode and update for big data compression** [121].

In this article, a low complexity compression and decompression procedure is proposed which allows for maximal (entropy limit) noiseless data compression while allowing the retrieval of data symbols by querying order compressed symbols, and similarly for data update.

- Journal paper. **Best information is most successful: mutual information and success rate in side-channel analysis** [937].

This work pushed forward the evaluation and consolidation of side-channel security of cryptographic implementations. From a protection perspective, it provides a best-practice guideline for the application of code-based masking.

- Technology transfer/Spin-off creation. **MIMOPT Technology**.
<http://www.mimopt.com>

MIMOPT develops innovative digital signal processing solutions for fiber optic communications. It was created in April 2021 by Ghaya Rekaya (ComNum team), Yves Jaouen (GTO team), and Akram Abouseif, their former PhD student, capitalizing on more than thirteen years of research work.

2.1.3 GTO Team

- Journal paper. **Quantum metrology using time-frequency as quantum continuous variables: sub-shot-noise precision and phase space representation** [268].

In this work, we study the role of the electromagnetic field's frequency on the precision limits of time measurements from a quantum perspective, using single photons as a paradigmatic system. We demonstrate that a quantum enhancement of precision is possible only when combining both intensity and spectral resources and, in particular, that spectral correlations enable a quadratic scaling of precision with the number of probes.

- Journal paper. **Dual polarization nonlinear frequency division multiplexing transmission** [277].

In this paper, we experimentally demonstrated the extension of NFDm from the single- to dual-polarization transmission for the first time, using the continuous spectrum in NFDm. We showed that NFDm outperforms the burst-mode OFDM, in transmission over long-haul normal dispersion fiber. This is a representative work on NFDm from the group members.

- Journal paper. **High-capacity free-space optical link in the mid-infrared thermal atmospheric windows using unipolar quantum devices** [270].

In this work, we demonstrated for the first time the possibility of building a long-range link using unipolar quantum optoelectronics operating at 9.3 microns for free-space applications. Two different detectors are used: an uncooled quantum cascade detector and a nitrogen-cooled quantum well-infrared photodetector. We evaluated the maximum data rate of our link in a back-to-back configuration before adding a unique Herriott cell to increase the length of the light path up to 31 m. By using pulse shaping, pre- and post-processing, we reached a record bitrate of 30 Gbps for both two-level (OOK) and four-level (PAM-4) modulation schemes for a 31-m propagation link and a bit error rate compatible with error-correction codes.

- Conference paper. **Relaxing dispersion pre-distorsion constraints of receiver-based power profile estimators** [290].

In this paper, we bring DSP-based power profile estimation methods a step closer to a convenient low-complexity and seamless adaptation in optical transceivers to monitor power losses over optical networks without the deployment of additional hardware.

2.1.4 LabSoC Team

- Journal paper. **AMULET: a mutation language enabling automatic enrichment of SysML models** [334].

This paper showcases our scientific contribution to the field of modeling and verification, particularly when security aspects are at stake. The formal definitions allow the definition of model mutations, which are then used to update the security mechanisms of the system under evaluation. AMULET is now part of TTool¹. Also, the use case of the paper was provided by Mines Saint-Etienne, taken from the IT'M Factory².

- Journal paper. **Multi-resource scheduling for FPGA systems** [329].

This work, done in collaboration with Nokia Bell Labs, tackles the dynamic scheduling of tasks on FPGA resources in the cloud and data centers environments. A fast scheduling algorithm named Slot is proposed and evaluated. Slot outperforms the state-of-the-art. With its near-optimal scheduling and fast run times, it is a promising solution for the effective management of reconfigurable resources in the cloud.

- Journal paper. **Autonomous systems for rescue missions: design, architecture and configuration validation** [337].

This article emphasizes the development of our Arcturius platform (rover), with gradual progress on how to efficiently implement smart management of this platform.

- Journal paper. **Compositional equivalences based on open pNets** [295].

This article, written in collaboration with Inria and ENS Lyon, provides a theoretical background for establishing a compositional verification platform. Compositional verification emerges as a powerful approach, based on the divide-and-conquer paradigm, to address the inherent challenge in verifying complex systems, namely the well-known "state-space explosion" issue.

2.1.5 RFM² Team

- Journal paper. **Taming Fabry–Pérot resonances in a dual-metasurface multiband antenna with beam steering in one of the bands** [626].

This paper takes place in the context of the growing demand for multifunctional antennas that can accomplish several missions with a single device. It proposes a multilayer antenna composed of an ultra-wideband radiating element placed between two metasurfaces, one serving as a reflector and the other as a superstrate. This work shows how the phenomenon of Fabry-Pérot resonances can be controlled, and the concept is validated with a low-profile multiband directional antenna operating for 5G/4G/Wi-Fi 2.4/5/6E, which achieves beam steering in 5G without disturbing the radiation patterns of other bands.

- Journal paper. **2D indoor localization resolution improvement using IR-UWB stepped frequencies signals** [616].

For indoor localization (monitoring of patients in hospital, securing firefighters in a building ...), the work published in this paper was focused on the proof of concept of a 2D Impulse Response UWB (Ultra Wide Band) Localization system allowing estimating the position of an active tag

¹<https://ttool.telecom-paris.fr/>

²<https://www.mines-stetienne.fr/recherche/plateformes/itm-factory/>

by a localization base station. By using the time pulse distortion for each frequency (3.5 GHz and 3.55 GHz), it is possible to obtain an improved resolution of ± 2 cm on the range and $\pm 2^\circ$ on angles measurement for a radial distance inside [1–2 m]. This work supports the realization of high-resolution localization systems without increasing the frequency bandwidth and compliance with the power spectral density (PSD) used in UWB.

- Journal paper. **Stochastic surrogate models of deformable antennas based on vector spherical harmonics and polynomial chaos expansions: application to textile antennas** [617].

A new methodology of statistical modeling of the Far Field (FF) radiated by antennas undergoing random variabilities has been presented in this paper and applied to a wearable textile patch antenna designed to cover the 2.4-2.5 GHz band and subjected to five random geometric and material parameters (stretching, bending, torsion, compression and crumpling). Comparison to the full-wave simulations shows that the derived surrogate model predicts the FF with good accuracy and an acceleration factor of 105. Such type of surrogate models could be beneficial not only for antenna design and optimization purpose, but also, e.g., for joint antenna channel stochastic analyses.

- Journal paper. **Sensor-aided EMF exposure assessments in an urban environment using artificial neural networks** [648].

The need to monitor human RF exposure increases as wireless networks are deployed. Addressing the continuing perception of risk from EMF exposure today requires numerous measures. In this work we sought a new approach, based on both artificial intelligence (artificial neural network) and measurements to map exposures, with a minimum of measurements in a 4G cellular network, operating at 2.6 GHz, located in a district of Paris. This study showed that this hybrid approach allowed good prediction, following these simulations a study is underway with real data.

2.1.6 SSH Team

- Journal paper. **A review of sparse recovery algorithms** [927].

This paper offers a thorough review of sparse recovery algorithms in compressive sensing theory and discusses challenges in matrix design and efficient signal recovery, along with applications and open research questions.

- Journal paper. **Self-secured PUF: protecting the loop PUF by masking** [916].

This paper investigates Physical Unclonable Functions (PUFs) for generating chip individual keys in low-cost IoT applications. The study analyzes side-channel vulnerabilities of the loop PUF, proposing a low-cost countermeasure based on temporal masking.

- Conference paper. **Quad-Approx CNNs for embedded object detection systems** [999].

To build Convolutional Neural Networks (CNNs) with low resource requirements of embedded computer vision applications such as object detection, we propose in this paper quad-approx networks. We first quantize the convolutional layers. Then, an approximate multiplier for this special quantized network is proposed. Both approximations are back annotated to the training process leading to no loss in overall precision.

Quad-approx networks and other related research results of the SSH team are integrated into a technology transfer project called ApproxNet.

- Scientific event. **International winter school on micro-architectural security (Mic-Sec 2022)**.

<https://rb.gy/ftlbdn>

The SSH team organized at IP Paris the Mic-Sec 2022 winter school on micro-architectural security, a pioneering event featuring top experts, and diverse attendees, showcasing advancements in hardware security.

2.2 Computer Science and Networks

2.2.1 ACES Team

- Journal paper. **An abstraction-refinement framework for verifying strategic properties in multi-agent systems with imperfect information** [9].

In this paper, we investigate the verification of Multi-Agent Systems against strategic properties expressed in Alternating-time Temporal Logic under the assumptions of imperfect information and perfect recall. To this end, we develop three-valued semantics for concurrent game structures upon which we define an abstraction method. We prove that concurrent game structures with imperfect information admit perfect information abstractions that preserve three-valued satisfaction.

- Conference paper. **Scheduling multi-periodic mixed-criticality DAGs on multi-core architectures** [52].

In this paper, we define a meta-heuristic to schedule multiprocessor systems composed of multi-periodic Directed Acyclic Graphs (DAGs) of MC tasks. This meta-heuristic computes the scheduling of the system in the high-criticality mode first. The computation of the low-criticality scheduling respects a condition on high-criticality tasks' jobs, ensuring that high-criticality tasks never miss their deadlines.

- Software platform. **RAMSES: refinement of AADL models for synthesis of embedded systems**.

<https://gitlab.telecom-paris.fr/mbe-tools/ramses-2>

This platform is dedicated to assisting in the design and development of critical embedded real-time embedded systems.

- Software platform. **Software Heritage**.

<https://www.softwareheritage.org/>

The mission of Software Heritage is to collect, preserve, and share all software that is publicly available in source code form, and to build a common, shared infrastructure at the service of industry, research, culture, and society as a whole.

- European patent. **Pairing Method** [42].

This patent is a result of a collaboration between the ACES team and EDF R&D, through the SEIDO joint laboratory. It relates to a method of secure pairing between connected objects.

2.2.2 C2 Team

- Conference paper. **Verifiable decentralized multi-client functional encryption for inner product** [79].

In CRYPTO 2018, we introduced decentralized multi-client functional encryption (DMCFE) which has become the standard primitive in the context of functional encryption for a multi-user setting. In this paper, we significantly improve DMCFE by introducing verifiability and build it from class-group based structure.

- Conference paper. **Partial key exposure attacks on BIKE, rainbow and NTRU** [77].

NIST³ has published the first standard for post-quantum secure encryption and signature. However, the security of these schemes was not carefully studied when the secret information is partially leaked due to a side-channel attack in the real world. In this work, we take three types of post-quantum cryptographic schemes as examples and carefully study their security when partial leakage of the secret key is present. Therefore, we provide an important reference for the security of post-quantum cryptography in the real world.

³National Institute of Standards and Technology, <https://www.nist.gov/>

- Conference paper. **Anamorphic encryption: private communication against a dictator** [80].

In this paper, we invented a new paradigm for protecting privacy under very strict conditions in the presence of a powerful adversary known as a dictator. Then, we developed further this work and published it in CRYPTO 2023 and PoPETs 2023. Our contribution has become now a standard cryptographic primitive.

- Conference demo paper. **Demonstrating internet of secure elements server** [81].

Internet of secure elements (IoSE) concept aims at deploying online secure elements, whose embedded resources are identified by dedicated Uniform Resources Identifiers. The first IoSE server was developed at the C2 team and presented at the IEEE CCNC conference.

- Book. **Introduction à l'optimisation continue et discrète** [75].

This book offers an introduction to optimization methods.

2.2.3 DIG Team

- Conference paper. **Dynamic membership for regular languages** [136]

The focus of the paper is on **dynamic membership**, a fundamental problem applicable to various contexts like streaming algorithms. The question is whether a word becomes to some regular language after successive character substitutions. Specifically, the objective of the paper is to identify regular languages for which dynamic membership can be solved very efficiently, e.g., in constant time.

- Conference paper. **Distributed approximate k-core decomposition and min-max edge orientation: breaking the diameter barrier** [164]

This paper provides distributed algorithms for solving NP-hard optimization problems in graphs with performance guarantees. The time complexity of the proposed algorithms is logarithmic in the number of nodes, and independent of the graph diameter.

- Knowledge base. **YAGO**

<https://yago-knowledge.org>

This is a general knowledge base with facts about millions of entities like people, cities, countries, movies, and organizations. It won the **Test of time award** at the Web conference in 2018 and the **French Open Science Award** in 2022.

- Software. **River**

<https://riverml.xyz>

This is an open-source Python library for online machine learning.

- Software. **Scikit-network**

<https://scikit-network.readthedocs.io>

This is an open-source Python library for graph learning.

2.2.4 DIVA Team

- Conference paper. **Skin-On Interfaces: a bio-driven approach for artificial skin design to cover interactive devices** [258].

In collaboration with ISIR⁴ (Sorbonne University) and Bristol University, this paper is one of the early publications of the ANR SocialTouch project. It explores the use of artificial, human-like skin for input. It demonstrates the team's blending of hardware and software prototyping in collaboration with ergonomic and social sciences research.

⁴Institut des Systèmes Intelligents et de Robotique, <https://www.isir.upmc.fr/>

- Conference paper. **The dark side of perceptual manipulations in virtual reality** [259].
This is an example of the team’s work in virtual and augmented reality. Perceptual manipulations are a common technique in virtual reality to create immersive experiences that overcome physical limitations in the environment. This work explores potential malicious uses of a useful technique to identify threats and risks as well as proposed mitigations.
- Software. **Webstrates**
<https://webstrates.net/>
This is both a vision and software platform for shareable, dynamic media, that reimagines the roles of application and document around sharing, collaboration, and software malleability. It has been under active research since 2012, in continuing collaboration with Aarhus University and LRI⁵ (Paris-Saclay University).
- Conference paper. **MobiLimb: augmenting mobile devices with a robotic limb** [257].
The ANR SocialTouch project opened a new research direction for the team drawing on the MobiLimb work. It focuses on the use of social touch-based interactions and led to the follow-on project, ANR SecondSkin.

2.2.5 QURIOSITY Team

- Journal paper. **Experimental investigation of practical unforgeable quantum money** [583].
This work demonstrates experimentally a quantum money protocol relying on classical verification that rigorously satisfies the security condition for unforgeability.
- Journal paper. **Homodyne detector blinding attack in continuous-variable quantum key distribution** [599].
This work analyzed and has experimentally demonstrated for the first time the existence of a critical attack path against continuous-variable QKDQuantum Key Distribution based on detector saturation, including its experimental exploitation, theoretical model, and countermeasure.
- Journal paper. **Long-range QKD without trusted nodes is not possible with current technology** [592].
This work done in partnership with key international leaders clarifies the conditions for long-range QKD.
- Journal paper. **Limitations of variational quantum algorithms: a quantum optimal transport approach** [588].
In this work, we obtain extremely tight limitation bounds for standard NISQ⁶ proposals for variational quantum algorithms in both the noisy and noiseless regimes, with or without error-mitigation tools. The bounds limit the performance of both circuit model algorithms, such as QAOA⁷, and also continuous-time algorithms, such as quantum annealing.

2.2.6 RMS Team

- Joint lab. **LINCS**
<https://www.lincs.fr/>
This is a joint academy-industry research and innovation Lab, active in the domain of future information and communication networks, systems and services. Its partners are Inria, Institut Mines-Télécom, Nokia Bell Labs, Sorbonne Université and SystemX.
Some of the fundamental subjects of the team are developed within the joint laboratories LINCS.

⁵<https://www.lri.fr/>

⁶Noisy Intermediate Scale Quantum

⁷Quantum Approximate Optimization Algorithm

- Software and technology platform. **Free 5G**
<https://www.carnot-tsn.fr/plateformes-technologiques/plateforme-free-5g/>
 This equipment consists of a Faraday cage (40 square meters), in which a complete 4G/5G system is deployed. This research platform makes it possible to perform experiments remotely at every level of a cellular system (RAN, Core Network) for a wide range of cellular technologies: 2G (GSM/GPRS/EDGE), 3G, LTE, NB-IOT, LTE-M, 5G NSA, 5G SA. Furthermore, it also provides usage of a wide range of communication technologies in other network domains such as WPAN (IEEE 802.15.4, Bluetooth LE), WLAN (Wi-Fi), and LPWAN (LoRa).
- Journal paper. **Diffusive limits of Lipschitz functionals of Poisson measures** [658].
 Continuous Time Markov Chains, Hawkes processes, and many other interesting processes can be described as solutions of stochastic differential equations driven by Poisson measures. Previous works, using Stein’s method, give the convergence rate of a sequence of renormalized Poisson measures towards the Brownian motion in several distances, constructed on the model of the Kantorovitch-Rubinstein (or Wasserstein-1) distance. In this paper, we show that many operations (like time change, convolution) on continuous functions are Lipschitz continuous to extend these quantified convergences to diffusive limits of Markov processes and long-time behavior of Hawkes processes.
- Journal paper. **A combined stochastic and physical framework for modeling indoor 5G millimeter wave Propagation** [689].
 Indoor coverage is a major challenge for 5G millimeter waves (mmWaves). In this paper, we address this problem through a novel theoretical framework that combines stochastic indoor environment modeling with advanced physical propagation simulation. This approach is particularly adapted to investigate indoor-to-indoor 5G mmWave propagation.
- Conference paper. **The long road to sobriety: estimating the operational power consumption of cellular base stations in France** [653].
 As the Information and Communication Technology (ICT) sector represents 1.8% to 3.9% of the global Green House Gas (GHG) emissions, it is of utmost importance to know how much energy is spent annually in mobile networks and how this consumption is evolving. It is quite likely that the huge energy efficiency gains achieved by technology evolution have at least been compensated by the surge in data traffic. Therefore, in this paper, we estimate the operational power consumption of cellular Base Stations (BSs) deployed in France from 2015 to 2022.

2.3 Image, Data and Signal

2.3.1 IMAGES Team

- Journal paper. **As if by magic: self-supervised training of deep despeckling networks with MERLIN** [377].
 This paper presents a very innovative method of self-supervised deep learning for SAR⁸ speckle reduction using the splitting in real and imaginary part of the backscattered electro-magnetic wave. It exploits the complex nature of the backscattered electro-magnetic signal by splitting it in real and imaginary part. One is given as input whereas the other one is used to compute the loss, allowing to train the network with the available SAR images without needing ground truth data. This strategy gives state-of-the-art speckle reduction results.
- Journal paper. **Fully synthetic training for image restoration tasks** [351].
 This work proposes to train neural architectures for image restoration tasks from purely synthetic data, leveraging simple geometric models adapted to the statistics of natural images. To the best of our knowledge, this is the first work that manages to completely bypass the need of real images for image restoration, including difficult real-world tasks such as RAW image denoising.

⁸Synthetic-Aperture Radar

- Journal paper. **Delaunay Painting: perceptual image colouring from raster contours with gaps** [446].

This work introduces Delaunay Painting, a novel and easy-to-use method for flat-color contour sketches with gaps, which is being commercialized. Relying on Delaunay triangulation, this method, as an interactive tool, minimizes the user's efforts and enables any coloring strategy as the result does not depend on the order of interactions.

- Conference paper. **Integrating prior knowledge in contrastive learning with kernel** [386].

This paper proposes a new decoupled contrastive loss that allows the integration of prior information, like auxiliary attributes or representations from generative models, into contrastive learning, to make it less dependent on data augmentation. We empirically show that our loss achieves State-of-the-Art results in the unsupervised and weakly supervised setting, using both medical and natural imaging datasets.

2.3.2 MM Team

- Software. **GPAC – Video streaming and next-generation multimedia transcoding, packaging and delivery.**

<https://gpac.io/about/>

GPAC Project on Advanced Content (GPAC, a recursive acronym) is an open-source implementation of the MPEG-4 Systems standard written in ANSI C. It provides tools for media playback, vector graphics and 3D rendering, MPEG-4 authoring, and distribution. During the period 2018-2020, GPAC has been completely reorganized to meet industrial and academic needs (GPAC Filters, MMSys 20) and is as of 2023 the main file packager of Netflix.

- Conference paper. **Mining bias-target alignment from Voronoi cells** [977].

Despite significant research efforts, deep neural networks remain vulnerable to biases: this raises concerns about their fairness and limits their generalization. In this paper, we propose a bias-agnostic approach to mitigate the impact of biases in deep neural networks. Unlike traditional debiasing approaches, we rely on a metric to quantify "bias alignment/misalignment" on target classes and use this information to discourage the propagation of bias-target alignment information through the network.

- Conference paper. **Few-shot semantic image synthesis with class affinity transfer** [487].

This work introduces a novel method based on transfer learning to train image generation models conditioned on semantic maps with few annotated samples. It is the outcome of a successful PhD in partnership with Meta. Semantic image synthesis aims to generate photo-realistic images given a semantic segmentation map.

2.3.3 S²A Team

- Journal paper. **Depth for curve data and applications** [778].

John W. Tukey (1975) defined statistical data depth as a function that determines the centrality of an arbitrary point with respect to a data cloud or to a probability measure. During the last decades, this seminal idea of data depth evolved into a powerful tool proving to be useful in various fields of science. Recently, extending the notion of data depth to the functional setting attracted a lot of attention among theoretical and applied statisticians. We go further and suggest a notion of data depth suitable for data represented as curves, or trajectories, which is independent of the parametrization. We show that our curve depth satisfies the theoretical requirements of general depth functions that are meaningful for trajectories. We apply our methodology to diffusion tensor brain images and also to pattern recognition of handwritten digits and letters.

- Journal paper. **Learning fair scoring functions: bipartite ranking under roc-based fairness constraints** [711].

In this paper, we study fairness for the problem of learning scoring functions from binary labeled data, a classic learning task known as bipartite ranking. We argue that the functional nature of the ROC curve, the gold standard measure of ranking accuracy in this context, leads to several ways of formulating fairness constraints. We introduce general families of fairness definitions based on the AUC and on ROC curves and show that our ROC-based constraints can be instantiated such that classifiers obtained by thresholding the scoring function satisfy classification fairness for a desired range of thresholds. We establish generalization bounds for scoring functions learned under such constraints, design practical learning algorithms, and show the relevance of our approach with numerical experiments on real and synthetic data.

- Journal paper. **Audio signal processing in the 21st century** [862].

This paper provides a view of the important outcomes of the field in the past 25 years, also illustrating the emergence of purely data-driven models. In particular, the article covers the research addressed in signal models and representations; the modeling, analysis, and synthesis of acoustic environments and acoustic scenes; signal enhancement and separation; music information retrieval (MIR); and detection and classification of acoustic scenes and events (DCASE).

- Conference paper. **Few-shot emotion recognition in conversation with sequential prototypical networks** [804].

In this work, we place ourselves in the scope of a live chat customer service in which we want to detect emotions and their evolution in the conversation flow. This context leads to multiple challenges that range from exploiting restricted, small, and mostly unlabeled datasets to finding and adapting methods for such context. We tackle these challenges by using Few-Shot Learning while making the hypothesis it can serve conversational emotion classification for different languages and sparse labels. We contribute by proposing a variation of prototypical networks for sequence labeling in conversation that we name ProtoSeq.

- Interdisciplinary center. **Hi! PARIS – Paris Artificial Intelligence for Society & Business**

<https://www.hi-paris.fr/>

Leadership role in Hi! PARIS (scientific and operational co-supervision, design and management of the Engineering Team).

- Industrial Chair. **DSADIS – Data Science and Artificial Intelligence for Digitalized Industry and Services**

<https://datascienceandai.wp.imt.fr/>

This teaching and research chair, held by Florence d’Alché-Buc, has been running for five years (2019-2023) and sponsored by Airbus Defence & Space, Engie, Idemia, Safran and Valeo, with a total budget of 2.2 M€.

- Technology transfer. **AHEAD – Augmented HEADphone experience**

This is a maturation project (i.e. geared towards technology transfer) funded by the SATT Paris Saclay⁹ (620 K€). It is aimed at the development of an intelligent headphones system and distributed audio recording infrastructure to offer sports events spectators an immersive audio experience of the game.

⁹<https://satt-paris-saclay.fr/>

Part II

TEAMS SELF-ASSESSMENT

Chapter 3

Self-assessment of C2S team

3.1 Profile, Resources and Organization

3.1.1 Scientific objectives

The C2S team aims to develop circuits and systems for communication. Our area of expertise is the hardware implementation of analog and mixed-signal (AMS) systems enhanced by digital algorithms. Our main objective is to fulfill application requirements while reducing power consumption.

We focus on three main research themes along with the corresponding developments:

- **Linearization techniques:** efficient models for RF power amplifiers and innovative digital pre-distortion techniques.
- **Innovative communication systems:** smart sensors for healthcare applications, intra-body communications for leadless pacemakers, novel transmitter architectures to process broadband signals and channel sensing.
- **Circuits for AI and AI for circuit design:** analog circuits for basic mathematical functions used in multi-layer perceptrons and joint design of circuit architecture and algorithms to perform on-chip training tasks.

3.1.2 Resources

C2S team members' competencies include transceiver architectures, analog and mixed-signal (AMS) circuits, algorithms, and circuit design through to physical prototypes, in addition to practical skills to perform analysis on real-world implementations. For this purpose, the team is composed of people with wide-ranging expertise, from algorithms to hardware design, in addition to a laboratory to carry out analytical work. Research is funded via several sources. Close links with the industrial world enable the team to work on a variety of CIFRE PhDs and collaborative projects.

- *Human resources:*

Team leader: Patricia Desgreys (FP).

Faculty: Paul Chollet (AP), Patricia Desgreys (FP), Chadi Jabbour (AP), Van-Tam Nguyen (FP, on leave from 2018 to 2021), Dang-Kiên Germain Pham (AP, 12/20–).

Research Engineers: Reda Mohellebi (RE, 04/20–), Dang-Kiên Germain Pham (RE, 11/17–11/20).

Invited Researcher: Oleg Vityaz (04/22–07/22).

PhD Students: Thuy Pham Trong (10/2022–), Duc Tuyen Ta (11/2014–07/2018), Akram Akbari (06/2023–), Joe Bachi (10/2018–11/2022), Antoine Back (10/2018–02/2022), Clément

Beauquier (01/2019–), Carolina Cavalcanti Pedrosa E Silva (11/2023–), Lyliya Chabane (10/2020–), Evelyn De Oliveira Lima (07/2023–), Fatma Kiraz (10/2021–), Zhu Lioa (09/2022–), Mirko Maldari (03/2017–05/2020), Mikhail Manokhin (10/2021–), Venkata N. Manyam (10/2015–11/2018), Meghna Mukhopadhyay (10/2023–), Rémi Nahon (11/2022–), Viet Nguyen (12/2023–), Aël Quélenne (12/2022–), Nicolas Schlegel (03/2023–), Marceline Tchambake Yapti (10/2014–08/2019), Yinghao Wang (09/2022–), Haoyang Zeng (10/2023–).

PostDocs: Tayeb Habib Chawki Bouazza (10/2022–/2024), Gabriel Souza Franco (10/2019–12/2019), Mirko Maldari (06/2020–12/2020).

- *Laboratory:*

The team operates within a collaborative environment, sharing an advanced electronics laboratory with the SSH team. The laboratory is equipped with an industry-grade platform designed to evaluate the linearity of power amplifiers and the effectiveness of DPD linearization techniques.

- *Financial resources:*

The team benefits from many types of research funding derived from both national and international sources.

Type	Number
Cluster Saclay	1
Bilateral	2
Chair & Commun Lab	1
CIFRE	3
European	1
IP Paris	2
Public (non ANR)	3
International Collaboration	1

2018-2023 (K€)							
	2018	2019	2020	2021	2022	2023	Total
Public National					74	195	269
International	9					9	18
Partnership & Transfer	87	78	65	78	120	205	633
Total	96	78	65	78	194	409	921

TABLE 3.1: C2S financial resources.

3.1.3 Human resources management, safety, environment, ethical protocols, data and scientific heritage protection

Team meetings take place every two months. Some additional meetings are scheduled for specific events such as the educational program.

The team is sensitive to gender equality. Patricia Desgreys is the Head of the C2S team. We recruit female students for internships and doctorates as often as male students.

Work is collaborative within the team and close attention is paid to the well-being of all members by ensuring respect in the workspace, adherence to work rules, and holding informal discussions daily.

3.1.4 Synthetic self-assessment

The team is at the forefront of research into specific topics related to new 5G/6G transceivers, energy saving, and AI development.

Strengths:

The C2S team brings together three highly qualified HDR researchers managing numerous innovative projects. We have just recruited a new research engineer with extensive experience in RF design and measurement, which is a positive complement to our areas of expertise. Many ambitious projects have recently been launched in collaboration with Télécom Paris, with partners from the Plateau de Saclay, at both national and international levels. We are confident in the future of our research thanks to the quality of our results and the ever-increasing demand for the industrial development of microelectronics in France and Europe.

Difficulties and solutions:

An important difficulty in microelectronics, corollary of the previous point, is the recruitment of outstanding doctoral students, as they are either quickly hired by industry if they are European, or they often do not meet the HFDS selection requirements if they come from non-European countries. Another difficulty is the duration of the doctorate: 3 years has always proved too short in order to create and measure a remarkable circuit. Our strategy in the face of these two difficulties is to start working on the thesis subject from the M2 year and to attract the best students into a research program from the M1 year.

Finally, the team faces challenges due to the rapidly changing technological landscape. The expertise required to develop advanced microelectronic chips is difficult to acquire and there is a notable shortage of young researchers interested in the field of microelectronics. This lack of interest makes it difficult to attract new talent. Additionally, excelling in machine learning (ML) requires a different set of skills, including exceptional mathematical abilities, especially in optimization, and excellent programming skills. These skills are often distinct from those needed in microelectronics. Balancing expertise across these different areas is a challenge for our team working at the intersection of these technologies.

Our strategy is to emphasize our collaboration with ML specialists within the LTCI and to continue to collaborate with manufacturers in the field of microelectronics to accelerate the realization of our design innovations into practical achievements.

3.2 Attractiveness

3.2.1 Scientific reputation and contributions

C2S Faculty members are involved in responsibilities within learned societies, in organizing conferences, and in editorial activities. Patricia Desgreys has been president of the IEEE CAS France chapter since 2015, as well as coordinator of the IEEE NEWCAS conference since 2020. Desgreys was chair of the technical program of the IEEE PRIME conference in 2019, and guest editor of the IEEE TCAS II in 2018 and 2019. Chadi Jabbour and Patricia Desgreys edited the book “Digitally Enhanced Mixed Signal Systems” published in 2019 by the company IET (Institution of Engineering and Technology).

The team is regularly invited to give tutorials at international conferences: IMS 2021, ISCAS 2019, ICECS 2018.

In addition, they participate in national research evaluation: HCERES evaluation committee for the XLIM laboratory in 2021, as well as several selection committees for the recruitment of professors, and numerous PhD and HDR juries.

3.2.2 Staff hosting policy

The team works largely with industrial engineers for both teaching and research projects. For this purpose, engineers from NXP, STM, and THALES come to work in our laboratory several times a year for several days (1 to 4 days).

We are also proud to regularly welcome professors on sabbatical leave. Even though circumstances

proved unfavorable in recent times due to the COVID-19 pandemic, we were able to welcome Professor Oleg Vityaz from the National Technical University of Ukraine in 2022.

During the period 2018-2023, we saw the arrival of 1 permanent Research Engineer in 2020, 4 non-permanent Research Engineers/Postdoctoral Researchers, as well as all doctoral students and interns. There are three times more young researchers than permanent professors.

Everyone benefits from a good working environment and cutting-edge equipment (computers, software, high level of IT resources) alongside an intensive team life with scientific seminars and informal exchanges.

3.2.3 Success in competitive calls for projects

The C2S team has enjoyed notable success in competitive calls for projects:

- At European level, the project Horizon2020 SHIFT was accepted in 2022
- At national level with PEPR 5G & Future Networks, BPI France DOCTE 6G, BPI France Beyond 5G
- At local level with the PREMAT 2 SATT Paris-Saclay project

3.3 Scientific Production

3.3.1 Qualitative analysis

Table 3.2 presents overall scientific production between 2018 and 2023. The detailed bibliography is listed in the dedicated accompanying document.

Journals	Articles in Proceedings	Books and Book Chapters	Patents	Habilitation thesis	Completed PhD
11	33	5	5	1	6

TABLE 3.2: Overall scientific production

Linearization techniques:

As wireless technologies continue to advance, so does the demand for high-performance RF power amplifiers (PAs) capable of handling wideband signals and delivering accurate linearity. The team explores linearizing techniques that both maximize linearity and efficiency performance and minimize hardware and complexity by exploiting cross-domain analysis.

For example, conventional memory polynomial (MP) models are now proving to be prohibitively complex in terms of implementation in real-time applications due to an increased number of system nonlinearity mechanisms. To address this, the team developed a novel approach that analyzes the circuit topology of the PA to produce a compact and accurate baseband model. This model captures the essential nonlinearities of the PA, while also being computationally efficient [104], [105].

Another challenge in linearizing PAs is the bandwidth of the signals they need to handle. Conventional DPD algorithms require a large bandwidth expansion, which can be inefficient and power-hungry. To address this, we have investigated the use of mixed-signal predistortion (MSPD) techniques. MSPD combines the advantages of both analog and digital processing. The low-power wideband analog components compensate for the nonlinear effects of the PA, while the accurate digital processing compensates for long-term memory effects. This approach can significantly reduce the bandwidth expansion requirements for digital-to-analog converters (DAC), making it more suitable for wideband applications [96], [95]. The bandwidth limitation of DPD is largely investigated by the team to reduce the design constraints of analog-to-digital converters. The team mainly focuses on subband processing which makes it possible to reduce sampling frequency

constraints but requires adequate signal processing to extract accurate linearizing models [102], [100], [103], [101]. Finally, the design of a PA module has been carried out by exploiting outphasing high-efficiency features. Preliminary analysis has been published to demonstrate the fundamental elements of the technique [82]. The PAM is implemented using two-stage DPA in a 130nm RF-SOI process. The PA reaches state-of-the-art circuits and achieves a measured peak PAE of 51% at 32dBm. It has been published in the top-ranked IEEE Transactions on Circuits and Systems journal [83].

Innovative communication systems:

The rapid development of wireless sensor networks and the Internet of Things (IoT) has led to a rapid increase in the number of connected devices, especially sensors. These sensors are deployed in many fields such as healthcare, transportation, industry, the military, and agriculture. Due to the wireless nature of the devices, information must be sent through the radio frequency spectrum leading to increasing constraints in bandwidth. Even though 5G and 6G developments aim to increase the capacity of wireless communication, it will not be sufficient to match the rate of increase in bandwidth requirement. Moreover, the transmission aspect of the sensors is the most energy-consuming, reducing their battery life. It seems then that sending less data from the sensors is a very promising solution, as it will increase the lifetime of sensors while reducing bandwidth constraints.

Our work aims to develop smart sensors able to adapt to their environment while always sending the least amount of data to perform the required task. Analog-to-Feature (A2F) conversion is a very good solution, as it only extracts useful features relevant to the specific task from the analog signal directly in the sensor node. The features are then used by a machine-learning model either on the sensor or after transmission. In this context, we worked on the design of a generic and reconfigurable architecture to perform A2F conversion for low-frequency (<100 kHz) signals. The architecture is based on non-uniform wavelet sampling and was evaluated for two applications: ECG arrhythmia detection and human activity recognition (HAR). The work on ECG [729] allowed us to obtain 98 % classification accuracy while extracting only 10 features. The estimated power consumption is only 3.3 μ J for the extraction. The energy requirement to process 10 seconds of data is divided by 15.3 compared to a classical approach that sends all the data. A similar study for HAR in [94] leads to a multiclass classification accuracy of 87.2 % while extracting only 16 features. The number of parameters in the resulting ML model is divided by 965 compared to the best-performing algorithm. The estimated power consumption is divided by 5.8 compared to simply sending all the data.

We also worked on intra-body communication (IBC) for leadless pacemakers and developed innovations both at the fundamental and application levels. Firstly, we created a methodology for galvanic IBC characterization for deep implant devices. The attenuation of the communication channels was characterized using an accurate torso model that was verified by means of in-vivo experiments [92]. This constitutes an important step for the design of efficient transceivers for IBC applications. Secondly, we designed an ultra-low power fully galvanic IBC transceiver for multi-node LCP synchronization. This system meets the specifications while reducing power consumption by a factor of 2 compared to the state-of-the-art. Furthermore, a new communication strategy was developed that effectively reduces the actual power consumption of intra-cardiac communication to 2% of the full-time use power consumption of the transceivers. This result makes it possible to operate the dual-chamber LCP at the expense of a 25% increase in the battery capacity of the LCP currently used [93]. This work was part of the multidisciplinary WiBEC European project aiming to develop wireless technologies for novel implantable devices.

The popularity of connected devices has led to an increase in global data traffic with higher constraints in terms of power efficiency, sensitivity, and linearity. To address these challenges, we proposed a novel transmitter architecture, which can generate a wideband signal (3 GHz), directly centered around a high-frequency carrier (28 GHz). Several challenges had to be faced to ensure the performance of this novel architecture. Firstly, we proposed a novel architecture for the duty

cycle controller (DCC) using the backgate feature of the 28 nm FDSOI technology employed. The proposed circuit corrects the input duty cycle by means of a negative feedback analog loop. Observability of the duty cycle is made through a passive low pass filter, with the control achieved by modifying the rise and fall time of the input clock signal, via backgate biasing of an inverter chain [86]. We also proposed a detection and calibration circuit for current sources of static mismatch introduced by a process of fabrication [85]. Using these 2 novelties, the transmitter was designed in the 28 nm FDSOI technology. The system achieves 8 bits of resolution with a linearity higher than 40 dB at 28 GHz with a power consumption of 60 mW.

Channel sensing is a fundamental task of modern radio receivers and consists of probing the channel from time to time to check whether or not it is active, e.g. because of an incoming message. When communication is sparse with small amounts of information sent at irregular intervals, channel sensing becomes a relatively significant source of energy consumption. To address this problem, we proposed a novel technique called AdaSense, which exploits the dependency between the receiver noise figure and receiver power consumption. AdaSense begins in a low power low reliability mode and makes a first tentative decision based on a few channel observations. If a message is declared, it switches to a high power high-reliability mode to confirm the decision, otherwise, it sleeps for the entire duration of the second phase. The sizing of each phase length and noise figure is performed on an optimal log-likelihood ratio analysis. When compared to prominent detection schemes such as the BMAC protocol, AdaSense provides relative energy gains that grow unbounded in the small probability of a false-alarm regime, as communication gets sparser. In the non-asymptotic regime, energy gains are 30% to 75% for a variety of practical communication scenarios typically found in the context of wake-up receivers [116].

Circuits for AI and AI for circuit design:

The implementation of machine learning (ML) calculations is typically performed using digital means (e.g. MCU, CPU, GPU, etc.). These digital implementations mainly use Von-Neumann computing architectures (where memory and computation unit are separated) which involve a prohibitive level of energy consumption due to data movements between the hardware units. Analog electronics offers several potential advantages over digital electronics for ML implementation, such as: lower power consumption, higher computational speed, and in-memory computing. The C2S team carried out research focused on the following areas: the design of analog circuits for basic mathematical functions used in multi-layer perceptrons and the joint design of circuit architecture and algorithms to perform on-chip training tasks. Preliminary analysis has been published at international conferences [88], [87], [90] focusing on the hardware sizing of an analog sigmoid gate, on hardware friendly weight update equation (aka Manhattan update rule, or sign-SGD) or analog based computation of weights gradients.

Analog integrated circuit design is widely considered a time-consuming task due to the acute dependence of analog performance on the transistors' and passives' dimensions. A large amount of research has been conducted in the past decade to reduce the front-end design cycles of analog circuits using various automation approaches. On the other hand, the significant progress in high-performance computing hardware has made machine learning an attractive and accessible solution for everyone. We have carried out a complete overview of the existing state-of-the-art machine learning techniques used in analog circuit sizing and analyzed their effectiveness in achieving the desired goals [97]. We are now focusing on providing solutions for open challenges such as designing switched systems (Mixer, switched capacitors), considering process variations, and adapting these approaches to more advanced CMOS nodes, especially FinFETs.

3.3.2 Potential and dissemination strategy

Dissemination efforts are dedicated to concretizing each novelty in a publication, presenting them in seminars, or securing a patent. Doctoral students are encouraged to first publish at a national conference (GdR SOC2) as well as an international conference during the first year of their doc-

torate.

In the second year, they produce at least one journal article on the study of the system and at an additional top-ranked conference in their field. During the third year, they are encouraged to publish another article in a journal presenting the final results of the doctorate.

In addition, our team organizes workshops (GdR and IEEE CAS) and international conferences (IEEE NEWCAS).

3.3.3 Scientific integrity, ethics and open science

The general policy of C2S is to release its contribution in an open science format. This includes project results, publications, and software, for example using dedicated GitLab repositories.

Our publications are accessible on the HAL open science website.

Additionally, the team has started publishing in open-access journals provided that the journal is highly reputed and fees are waived by the publisher.

3.4 Contribution of Research Activities to Society

3.4.1 Socioeconomic partnerships and interactions

Our relationships with manufacturers are manifold and essential. During the period 2018-2023, we collaborated on 4 PhDs directly supported by key players in the industrial sector: Microport collaboration, M. Maldari (2017-2020), CEA collaboration, J. Bachi (2018-2021), CIFRE STMicroelectronics, C. Beauquier (2019-2022), CIFRE Nokia Dell Labs, N. Schlegel (2023-2026), CIFRE Nokia Dell Labs, A. Akbaril (2023-2026).

We collaborate in continuing education initiatives with MASTER in Embedded Systems (2018-2022), in addition to collaborative science activities with the LESIA, and are also involved in open-source projects (PySpice, Pysmu).

3.4.2 Research valorization and transfer

A significant proportion of the research results produced during the collaboration can be used in products improving the competitiveness of our industrial partners.

We participated in 5 patents supported by manufacturers over the period.

3.4.3 Science popularization

Actions are carried out to promote science among young women. In particular, Patricia Desgreys presented her scientific career and her motivations to high school female students during a "journée de sensibilisation et de découverte des métiers d'ingénieur.euses du numérique à destination de collégiennes et lycéennes".

Chapter 4

Self-assessment of ComNum team

4.1 Profile, Resources and Organization

4.1.1 Scientific objectives

The ComNum team, renowned for its works in information theory, coding theory, and applied mathematics, continues to push the boundaries of what is possible in the realms of information storage, transmission, and security, and other applications of centralized or distributed information processing such as distributed detection, sensing, guessing, distributed computing, or coordination of smart agents. Our research elucidates fundamental limitations in such systems, focusing on critical parameters such as information rate, accuracy, reliability, latency, and energy consumption. By developing innovative theoretical frameworks and practical algorithms, we address the intricate balance between these factors, ensuring efficient information processing systems.

Over the last years, the team has substantially diversified its portfolio and shifted the focus from considering only data transmission systems to all kinds of information processing systems including machine learning applications, cryptographic primitives, or detection systems. Within the vast area of communication, we prominently remain active in the fields of wireless communication, fiber-optical communication, free-space optics, and satellite communication, as well as sporadic IoT communication.

Our objective is to maintain and enhance our global reputation, driving forward the frontiers of knowledge and technology by continuously exploring the interplay between theory and practical applications. We challenge the basic assumptions of classical models and introduce new theoretical frameworks to foster groundbreaking advancements in our fields of expertise. Oftentimes, our research directions are inspired by practical considerations and timely research problems, for example, related to the emerging 6G communication standard, requirements on future cloud storage systems, or advanced security requirements.

4.1.2 Resources

- Human resources:
 - **Team leader:** Philippe Ciblat (FP until March 2021), Ghaya Rekaya (FP, since April 2021).
 - **Faculty between 2018 and 2023:** Philippe Ciblat (FP until June 2023), Olivier Rioul (FP), Aslan Tchamkerten (FP), Michele Wigger (FP), Hadi Ghauch (AP November 2018), Robert Graczyk (AP since December 2021).
 - **Invited Professors:** Karim Zayana (2018-2023), Patrick Solé (2020-), Victor Rabiet (2022-).
 - **Associate Researcher (with SSH team):** Wei Cheng (2022-2023).
 - **Sabbatical Professors:** Mohamed-Oussama Damen (2018, Waterloo University, Canada).

- **PhD Students:** Alexander Schaub (Defended December 2020), Mohamed Achraf Ksiba (Defended March 2018), Akram Abousseif (Defended July 2020), Mehrasa Ahmadipour (Defended November 2022), Laure Aptel (Phd stopped) Aymen Askri (Defended April 2021), Apostolos Avranas (Defended for June 2020), Julien Béguinot (Defended for 2025), Abir Ben HAdj Fredj (Defended June 2019), Yue Bi (Defense scheduled for 2025), Abdelaziz Bounhar (Defense scheduled for December 2024), Thomas Chêne (Defense scheduled for April 2025), Wei Cheng (Defended December 2021), Vincent Coraly (Defended December 2020), Pierre Escamilla (Defended December 2019), Ibrahim Fawaz (Defended December 2019), Samet Gelincik (Defended December 2019), Abdelghani Ghanem (Defense scheduled for 2025), Joana Girard-Jollet (Defense scheduled for May 2024), Julien Gori (Defended December 2018), Mustapha Hamad (Defended December 2022), Sebastien Huot (Phd stopped), Alaa Khreis (Defended December 2018), Mohamed Aymen Ktari (Defended December 2023), Guillaume Larue (Defended January 2023), Xavier Letruc (Defended January 2018), Long-guang Li (Defended July 2019), Yi Liu (Defended November 2023), Wanyu Liu (Defended November 2018), Perrine Lognoné (Defended December 2023), Arthur Louchart (Defended December 2021), Alix May (Defended April 2023), Sylvain Nerondat (Defense scheduled for 2025), Homa Nikbakht (Defended December 2020), Adil Salim (Defended November 2018), Xiaolin Wang (Defense scheduled for 2025), El Mahdi Amhoud (Defended January 2018), Éloi de Cherisey (Defended December 2018), Fatemeh Asgari (visiting PhD, 2018/2019), Haoyue Tang (visiting PhD, 2019/2020), Xiaolin Wang (Defense scheduled for 2025), Pierre-Augustin Berthet (Defense scheduled for 2025).
- **Post-Docs:** Chao Zhang (2020), K. G. Nagananda (2018-2019), Qifa Yan (2017-2019, now a professor at Southwest JiaoTong University), David Kibloff (2020-2021), Shuai Ma (2021-2023, now a professor at China University of Mining and Technology), Manuj Mukherjee (2018-2020, now a professor at IIT Delhi), Shashank Vatedka (2018-2019, now a professor at IIT Hyderabad).
- **Research Engineer:** Alfred Sawadogo (2019), Othmane Oubejja (2020).

Faculties	PhD students	Post-Docs	Engineers	Invited members
7	42	7	2	3

- **Financial Resources:**

Our financial strategy involves diversifying our funding sources—national and international, academic and industrial—to support research that spans both fundamental and applied aspects. Between 2018 and 2023, our research team has secured over 2.5 million euros from a variety of funding sources, enabling us to pursue cutting-edge projects and maintain our position at the forefront of our field.

4.1.3 Human resources management, safety, environment, ethical protocols, data and scientific heritage protection

- **Scientific seminars:** A monthly seminar is organized where PhD candidates and Post-Docs present and share their new results with all team members. These seminars are fertile grounds for exchanging and challenging ideas, fostering a collaborative environment. Additionally, these gatherings are convivial events that help build strong relationships within the team. Beyond these internal seminars, we regularly host seminars with external visitors to broaden our perspectives and collaborations.
- **Team meeting:** We also organize regular meetings for permanent team members to address academic, research, and administrative issues.
- **Gender equality:** The underrepresentation of women in engineering schools and our field is a significant challenge. Currently, our team comprises 1/3 women, which is higher than the average (around 1/5).

- Sustainable development charter: Aligned with the laboratory's policy, our team is fully committed to sustainable practices. One measure we implement is limiting conference travel by ensuring only one author attends each conference.

4.1.4 Synthetic self-assessment

Our research team is composed of researchers who are very well-established in their respective scientific communities and boast outstanding research achievements according to their publication records. The ComNum team excels at bridging the gap between theoretical and applied research, as demonstrated by our publications in top theoretical journals as the IEEE Transactions on Information Theory, and our various industrial collaborations and patents.

4.2 Attractiveness

4.2.1 Scientific reputation and contributions

Between 2018 and 2023, our team has maintained a high publication rate in leading journals and conferences in our main research areas, including Information Theory and Communication Theory. Our work has been recognized with several Best Paper Awards. Notably, one of our faculty members was recently awarded an ERC Consolidator Grant, following the successful completion of an ERC Starting Grant (2017–2022). Additionally, we are very active in filing patent applications and in the valorization of our research work, ensuring that our innovations have practical impact and commercial potential.

- Contributions and service by team members as part of IEEE Societies:
 - Member of the Board of Governors (BoG) of the IEEE Information Theory Society (Jan. 2017-Dec. 2019),
 - TPC Co-Chair of the 2023 IEEE Information Theory Workshop,
 - Distinguished lecturer of the IEEE Information Theory Society 2022-2023,
 - Associate Editor: IEEE Transactions on Information Theory, IEEE Transactions on Signal and Information Processing over Networks, IEEE Journal on Selected Areas in Information Theory,
 - Member of Technical Committee on "Signal Processing for Communications and Networking" for IEEE Signal Processing Society,
 - Member of the Editorial Board of Entropy "Information Theory, Probability and Statistics" (2023-),
 - Co-organizer of the 2019 IEEE Information Theory School,
 - Member of IEEE Information Theory Paper Award Committee (2018-2019),
 - Member of IEEE Information Theory Thomas M. Cover Dissertation Award Committee (2019–2020),
 - Member of IEEE Information Theory Diversity and Inclusion Committees, (2020-2022).
- Service to national organizations:
 - Member of the ANR project evaluation committee (2019-2021),
 - Member of the GdR ISIS Best Thesis Award committee (2019-2020),
 - Deputy Scientific Director for DigiCosme, LABEX Project (2016-2020),
 - Member of the GRETSI Best Thesis Award Committee,
 - Secretary and BoG of GRETSI,
 - Head of a research area of the GDR-ISI (2017-2021).

- TPC: ISIT, ITW, GLOBECOM, ICC, ICASSP, (among others).
- Sabbatical stays for faculty members:
 - One-month stay at Anhui University, China (2019): Olivier Rioul,
 - Three-month stay at Unicamp, São Paulo State University, Brazil (2020): Olivier Rioul,
 - Two-month stay at MIT, USA (July/August 2022): Robert Graczyk,
 - One-year sabbatical stay at the University of Zurich and ETH Zurich, Switzerland (August 2022-July 2023): Michèle Wigger.
- Invited talks, Keynotes:
 - IMT Toulouse, January 2018,
 - Entropy Conference, May 2018, Barcelona, Spain,
 - Workshop on Signal Processing, Communications, and Information Theory, September 2018, Spain,
 - Bourbaphy (Poincaré Seminar) on Entropy, November 2018, Paris,
 - Nokia Workshop, September 2018, Paris,
 - Huawei Paris Workshop, April 2019, Versailles,
 - London Symposium on Information Theory, May 2019, London, UK,
 - Network World Forum From Huawei, October 2019, Chengdu, China,
 - GDR-ISI Workshop, October 2019, Paris,
 - Invited paper at Asia Communications and Photonics Conference, November 2019, Chengdu, China,
 - Keynote at the Bombay Information Theory Seminar 2020, January 2020, Mumbai, India,
 - Keynote speaker at Research days of Ecole Supérieure des Communications de Tunis, February 2020, Tunisia,
 - Institut Polytechnique de Paris, Electrical Engineering AI Day, November 2020, Paris,
 - "Journées Partenaires Entreprises", November 2020, Télécom Paris,
 - University of Zurich, November 2021,
 - Virtual Workshop on Information Theoretic Limits and Signal Processing Techniques for Integrated Sensing and Communication, January 2022,
 - LACGA, Université Cheikh Anta Diop Dakar, February 2022, Senegal,
 - New Mathematical Techniques in Information Theory, Oberwolfach Research Institute for Mathematics, March 2022,
 - Collège de France, March 2022, Paris,
 - MaxEnt conference, July 2022, Paris,
 - Massachusetts Institute of Technology, July 2022, USA,
 - VIASM Hanoi, Aug. 2022, VietNam,
 - Huawei STW, online, September 2022,
 - King's College, October 2022,
 - Imperial College, October 2022, UK,
 - Cambridge University, October 2022, UK,
 - ETH Zurich, November 2022,
 - ICE Department, Institut Polytechnique de Paris, January 2023,
 - Information Theory and Tapas Workshop, Charles III University of Madrid, January 2023,

- Workshop "Performance Guarantees in Wireless Networks", Télécom Paris, March 2023,
- IMS Bordeaux, June 2023,
- ICCSM & ICEDL 2023, July 2023, Paris,
- 2023 IEEE European School of Information Theory, July 2023.

4.2.2 Staff hosting policy

The two most recent faculty members to join our team, in 2018 and 2021 respectively, are both young researchers. To give them ample time to familiarize themselves with the laboratory's and institution's operations and to establish themselves within the team, their teaching responsibilities have been reduced. Additionally, we are encouraging them to co-supervise PhD students. For example, Hadi Ghauch was involved in supervising two PhD theses during his second year at Télécom Paris. We also support their efforts to establish new national and international collaborations; for instance, Robert Graczyk spent two months in the summer of 2022 at MIT.

Our team is actively engaged in numerous national and international collaborations and frequently hosts visiting researchers. Professor Oussama Damen from Waterloo University, Canada, spent three months with us from April to July 2018. Unfortunately, due to the difficulties and restrictions resulting from the COVID-19 pandemic, our hosting arrangements were temporarily suspended.

4.2.3 Success in competitive calls for projects

The team is engaged in searching for funding at all kinds of levels and institutions. In particular, we have successfully attracted European funding (ERC Starting and Consolidator Grants), national funding (ANR projects, PEPR 5G), funding from local academic institutions (such as DigiCosme), thematic funding bodies (such as Hi! PARIS), industrial funding (ONERA, CNES and various CIFRE Contracts), as well patent-oriented funding (France Brevet).

More specifically, most of the PhD students and PostDocs hired in our team were paid from one of the following sources:

- ERC starting grant (CTO Com, 2017-2022) and ERC Consolidator Grant in the 2023 Call,
- ANR Projects,
- Patent Factory projects funded by France Brevet and Nokia,
- Several CIFRE contracts (Orange, Mitsubishi, Nokia, etc.),
- Hi! PARIS PhD funding,
- Futur & Ruptures IMT PhD funding,
- DigiCosme PhD funding,
- "Projets de prématuration" funded by Télécom Paris,
- Collaboration with ONERA and CNES.

European contracts	ANR contracts	CIFRE	Bilateral contracts	Phd fundings
1	3	8	4	9

4.2.4 Equipment quality and technological skills

The team's research primarily focuses on theoretical developments, validated through mathematical proofs and numerical simulations. To ensure the applicability of our results on real practical applications, we also specifically implement some of our findings on real testbeds. The ComNum team does not have its own testbed but instead can use testbeds at partner institutions. These collaborations enable us to bridge the gap between theory and practice, ensuring the practical applicability of our research findings.

For example, in partnership with the GTO team, we have tested our new code construction for optical communication on the optical experimental platform at the University of Lille. Additionally, as part of the ERC CTO program, we specifically hired a PostDoc and a research engineer to implement and test our coding idea for cache-aided networks on the CorteXLAB testbed at INSA Lyon. The results allowed us to validate the superior performance of our proposed code construction over previous coding schemes in a more realistic environment.

4.2.5 Synthetic self-assessment

The team members are well-established in their respective scientific communities and the ComNum team has an excellent reputation both on a national and international level. This is evidenced by important national and international funding achievements (ERC, ANR) and best paper awards, as well as by invitations for sabbatical stays at leading global universities, and the active roles our team members hold as TPC chair, associate editors, or lead guest editors in top international conferences and journals.

Despite the challenges posed by the COVID-19 pandemic, we successfully hosted several national and international speakers on various topics, thus further fostering our prestigious international reputation.

Our team's attractiveness is further highlighted by the recruitment of outstanding PhD students through master's programs like our own MICAS program and the institute's PhD track.

4.3 Scientific Production

4.3.1 Qualitative analysis

The main focus of the team's research efforts is on advancing the theoretical foundations and practical applications of information and coding theory, signal processing, and learning. An emphasis is placed on network information theory, coding for various (multi-user) communication setups, signal processing techniques for modern communication systems, security and cryptography applications, as well as statistical learning. The breadth and depth of the team's research topics are reflected in their publication record: Approximately one in six journal publications (17) appeared in the IEEE Transactions on Information Theory, considered one of the premier journals in the field of communications, coding theory, and signal processing. The team has published a total of more than 100 journal articles, covering a wide range of topics from optics, 5G-6G communications, distributed computation, compression, simulation, and security. The team's publication record also demonstrates its commitment to contributing to science through publications (including in French) and participation in dedicated conferences abroad as well as in France.

Research Focus Areas:

- **Network Information Theory:** The team is actively involved in characterizing the fundamental limitations of emerging communication setups such as coded caching, bursty communication, integrated sensing and communications, distributed detection, and optical communication. Research in this area also aims to develop novel coding schemes and protocols to enhance the efficiency and reliability of communication networks under various constraints and scenarios.
- **Information Inequalities:** Motivated by practical security frameworks, the team investigates information inequalities, particularly in the context of side-channel attacks. By developing rigorous mathematical frameworks and analysis techniques, the team aims to uncover vulnerabilities in communication systems and devise strategies to mitigate the risks associated with information leakage and unauthorized access.
- **Coding Theory:** In the realm of coding theory, the team's contributions span a diverse range of setups, including optical channels, distributed compression, and distributed computation.

Through theoretical analysis and algorithmic design, the team explores innovative coding techniques tailored to specific communication scenarios, with a focus on optimizing performance metrics such as reliability, throughput, and latency.

- **Signal Processing:** The team's expertise in signal processing extends to resource allocation for next-generation 5G and 6G networks. Leveraging techniques from machine learning and optimization, the team develops intelligent algorithms for dynamic resource allocation, spectrum management, and interference mitigation, aiming to maximize the efficiency and spectral utilization of modern communication systems.

4.3.2 Potential and dissemination strategy

The team is composed of senior and junior members. Accordingly, the senior team members often support their junior counterparts in the development of their activities by writing joint project proposals as well as joint student supervision. In addition, junior members enjoy a lighter teaching load. This policy helps junior members to establish themselves, as evidenced by their future career trajectories.

4.3.3 Scientific integrity, ethics and open science

The general policy of the team is to remove any barriers to scientific contributions. Accordingly, the majority of its publications are available to the general public (as part of the institution, all publications are on the HAL open archive). The team adheres to the guidelines of reproducible research and limits submissions to predatory journals/conferences.

4.3.4 Synthetic self-assessment

The team exhibits notable strengths, prominently characterized by its extensive publication records. Senior faculty members actively contribute to the academic development of the junior faculty, fostering collaborative efforts through joint project proposals and shared student supervision. The cultivation of mentorship and a supportive environment is evident, reflected in the comparatively lighter teaching load for junior members, providing them with opportunities for focused research and professional growth. However, the challenges posed by the recent global pandemic have impacted junior faculty's scientific output, highlighting the need for strategic adaptations to mitigate such external disruptions. Recognizing and addressing these challenges will be crucial to maintaining the team's overall excellence and sustaining a balanced scholarly output across all levels.

4.4 Contribution of Research Activities to Society

4.4.1 Socioeconomic partnerships and interactions

Over the years, the ComNum team has built up a solid relationship with renowned Telecom companies. For example, we have been working with Orange, Thales, and Nokia for over 20 years. We have also initiated new collaborations, with leading industry players Huawei and SecureIC. These collaborations take the form of bilateral research contracts and CIFRE contracts. Over the past four years, these collaborations have totaled some 17 contracts. Such partnerships are regarded as highly strategic by all team members, enabling us to keep abreast of technological challenges in the field.

The team is also involved in 3 Continuing Education courses, "Connaissance des lois des communications numériques", "Principe des Communications Numériques", "le codage canal"

We are also providing a course, "Comment devenir un chercheur inventeur", as part of the PhD training Program offered to PhD students.

4.4.2 Research valorization and transfer

The ComNum team is deeply committed to bridging the gap between fundamental and applied research. To achieve this, we maintain close interactions with industrial partners, engaging in collaborative projects and co-supervising PhD candidates. Furthermore, we regularly invite professionals from companies such as Nokia, Ericsson, Orange, and Huawei to deliver seminars to our students, providing them with valuable industry insights.

In addition to disseminating our research through publications, we actively promote our work by filing patent applications. Notably, our "Patent Factory" projects have seen significant success, resulting in the filing of over 10 patents in the past four years.

In 2021, a spin-off called MIMOPT Technology was established to capitalize on more than 15 years of collaborative research between the GTO and ComNum teams. Founded by Professor Ghaya Rekaya from our team, Professor Yves Jaouen from the GTO team, and their former PhD student, this start-up aims to commercialize innovative digital signal processing solutions for optical communications.

Since 2017, the team has offered a course titled "Innovation Technologies" tailored for Télécom Paris students. This course, designed to provide insights into innovation from the perspectives of researchers, inventors, and entrepreneurs, has been met with resounding success. Each year, the course reaches its maximum capacity, and student feedback remains consistently positive, highlighting its relevance and impact.

4.4.3 Science popularization

Our team has been very active in science popularization, addressing a variety of different audiences through publications and seminars. A list of our initiatives can be found below.

- Participation in national science dissemination initiatives:
 - Île-de-France representative for the Blaise Pascal Foundation, whose mission is to support and promote the dissemination of scientific culture in mathematics and computer science for young people, girls, and audiences deprived of access to scientific culture (2018-2023),
 - Participation in Fourier 250 activities (2018).
- Publications for popularization purposes:
 - Commented translation into French of Shannon's seminal book "A Mathematical Theory of Communication": "La théorie mathématique de la communication", Cassini, preface Olivier Rioul, Apr. 2018,
 - Translation into Portuguese of "Théorie de l'information et du codage": "Teoria da informação e codificação", O. Rioul, Sept. 2018 for science popularization purposes among Brazilian students,
 - French mathematical articles and blogs for "Collèges, Lycées, and Classes préparatoires": Bibnum Education (Jan. 2018), Bulletin de l'Union des Professeurs de classes préparatoires Scientifiques (Sept. 2019), Au Fil des Maths, Bulletin de l'APMEP (Sept. 2023), Tangente magazine (Sept. 2023), CultureMaths ENS (Jun. 2020, May 2021, Jun. 2021, Jan. 2022, Nov. 2022, May 2023),
 - Tutorial research articles, e.g. "This is IT: A Primer on Shannon's Entropy and Information", Chap. 2 in Information Theory, Progress in Mathematical Physics, Birkhäuser, Springer Nature, pp. 49-86, Aug. 2021,
 - Pedagogical textbook on parametric estimation, Spartacus IDH, September 2022.
- Seminars for large audiences:
 - Participation in MASA (Meeting on Algebraic Structures and Their Applications) for Pi Day, March 14, 2021,

- Nuit de l'ENS 2022 on "Uncertainty", presentation: "La connaissance réduit l'incertitude: polysémie en mathématique",
- Organization of the Probability History weekly seminar at ENS Paris (2021-22), presentations on Cardan, Bertrand, Kolmogorov, . . . ,
- MasterClass at Forum International de la Sécurité, 2023,
- Meeting with young high school students visiting Télécom Paris (2022,2023),
- Presentation of Digital Communications to several school groups,
- Hosting young trainees from high school.
- Math club for high school students:
The "Sublimaths" club (<https://sublimath.rezel.net/>) hosts since 2022 weekly mathematical workshops tailored for high school students. Our primary goal is to introduce participants to the beauty and elegance of mathematical reasoning, nurturing clarity of thought while equipping them with resources to explore deeper concepts through readings, videos, competitions, and more.

4.4.4 Synthetic self-assessment

The ComNum team is deeply engaged both within and beyond the academic sphere. Our close collaboration with leading companies and esteemed universities in France and abroad underscores our commitment to fostering strong ties across academic and industrial ecosystems, facilitating dynamic knowledge dissemination.

Recognizing the increasing demand from students for research that addresses human concerns, particularly in the face of pressing global challenges such as climate change and personal privacy, we are dedicated to infusing our research and teaching endeavors with meaning and purpose. By aligning our efforts with these critical global issues, we strive to empower our students and researchers to make meaningful contributions to the world.

Chapter 5

Self-assessment of GTO team

5.1 Profile, Resources and Organization

5.1.1 Scientific objectives

The Optical Communications team (GTO) is home to the research programs of nine faculty members and a research engineer. The GTO team conducts a broad range of research in photonics, spanning four research areas.

Area 1 (Quantum technologies, devices and communications) is focused on the design of new sources of squeezed light, encoding schemes for quantum communication protocols, and quantum key distribution (QKD), particularly in coexistence with classical communications. We contribute to the foundations of quantum optics and novel paradigms in quantum metrology, as well as participating in the construction of a three-node QKD network as part of a joint research project involving Télécom Paris, Orange and the LIP6 research institute.

Area 2 (High-speed digital optical fiber transmission) explores the information-theoretic limits of nonlinear fiber-optic channels, as well as digital signal processing (e.g. based on neural networks) and error-correcting codes to estimate the fundamental limits. Furthermore, we design novel signaling schemes tolerant to nonlinear effects in optical fibers with probabilistic and geometric shaping, as well as advanced DSP algorithms for space-division multiplexing (SDM).

Area 3 (Semiconductor lasers, optoelectronics, nonlinear photonics) has produced a number of breakthroughs in applied physics, as well as the development of proofs of concept and prototypes of next-generation photonics devices, with applications ranging from optical communications, sensing and photonic computing to defense and security. This research entails a broad spectrum of skills, from the assessment of material properties and modeling quantum devices to the theoretical analysis of functional devices.

Area 4 (Optical networks, monitoring and sensing) explores the cross-layer optimization of networks incorporating all-optical functionalities to increase capacity and lower energy consumption. DSP and machine learning are also applied for real-time diagnostics and the reconfiguration of optical networks. In addition, our team works on optical fiber sensing to monitor the telecom infrastructure or environment, in collaboration with national industrial partners.

Experimental demonstration of novel concepts in optical communication is of strategic importance to GTO. Thanks to a state-of-the-art experimental laboratory platform, we have demonstrated novel quantum key distribution protocols, photonic devices, nonlinear secure transmission schemes utilizing photonic chaos, and fiber sensors. GTO is a partner in CMA QuantEdu, an ANR-funded project for providing education in quantum technologies.

5.1.2 Resources

Team leader: Yves Jaouen (–2023), Frédéric Grillot (2023–).

Faculty: Élie Awwad (Associate Professor, October 2019), Nicolas Fabre (Associate Professor, December 2022), Renaud Gabet (Associate Professor), Frédéric Grillot (Full Professor), Heming Huang (Research Engineer), Yves Jaouën (Full Professor), Bruno Thedrez (Design Engineer), Cédric Ware (Full Professor), Mansoor Yousefi (Associate Professor, May 2016), Isabelle Zaquine (Full Professor).

Post-docs and senior researchers: Alex Chedid (2023-2024), Jianan Dian, Bozhang Dong, Pallab Kumar Choudhury (2023-2024), El Mehdi Amhoud (2018), Olivier Spitz, Kevin Schires, Alireza Tasdighi (2022-2024), Milad Sefidgaran (2019-2021), Chaima Zidi (2020-2021).

PhD students: Thomas Pousset (2023–), Hyunah Kim, Mingzhao Shi, Nour Nawfal, Emmanuel Bourgon, Alberto Breton, Zhangdi Chen, Sara Zaminga, Di Cui, Thibaut Renaud, Shihao Ding, Shirley Prado De La Cruz, Antoine Henry, Jingtian Liu, Xiaoyan Ye, Louis Tomczyk, Henrique Pavani Pereira Ramos, Isaia Andrenacci, Steren Guerrier, Alix May, Peter Nwakamma, Venkata Virajit Garbhapu, Jianan Duan, Antonin Gallet, Jean-Maxime Sarraute, Clement Romano (2014-2018), Bing Han (2014-2018), Wei Wei (2015-2018), Wasyhun Gemechu (2016-2019), Jan-Willem Goosens (2017-2020), Akram Abouseif (2017-2020), Pierre Clement (2017- 2020), Laurie Pailier (2017-2020), Abtin Shahkarami (2019-2022), Raphaël Aymeric (2018-2022), Jamal Darweesh (2020-2023), Mohammad Abu-Romoh (2019-2023), Jingtian Liu (2020-) Guillaume Ricard (2021-), Meghna Mukhopadhyay (2023–), Marco Andersohn (2022–).

Funding and contracts: Futur et Rupture (IMT), FUI Efflam, European Projects (QSNP, AI-NET), CIFRE Grants, National Projects (ANR QuantEdu, ANR CalQ, FUI EFFLAM), IP Paris Grants (Prematuration grant), Grants from US Federal Agencies (AFSOR, ONRG), H2020 MSCA-ITN-EID FONTE, H2020 MSCA-EID REALNET, ERC Starting Grant COMNFT, H2020 PICS4ALL, International Franco-German Program PhC Procop, Franco-Dutch PhC VanGogh (TU/e), Grants from industrial partners (HPE).

5.1.3 Human resources management, safety, environment, ethical protocols, data and scientific heritage protection

- Increasing the use of train travel to attend conferences, and prioritizing local European conferences whenever possible.
- considering the purchase of refurbished laboratory equipment when it is possible.

5.1.4 Synthetic self-assessment

Strengths

- team members regularly publish in top-tier journals and at conferences, including IEEE Transactions and other IEEE journals, in addition to print and online publications produced by Nature Portfolio, Optica, AIP, APS, and IoP, among others.
- The team members closely collaborate in joint projects alongside other institutions in France (Orange Labs, Exfo, Thales, Onera, Nokia Bell Labs, Huawei, SNCF, Ariane Group, mirSense, Febus Optis, 3SP Technologies, Mitsubishi, Inria, University of Nice, CEA Saclay, University of Paris, ENS, CNRS), in Europe (e.g. the UK, Germany, the Netherlands, Denmark, Italy, Spain and Poland, including institutions such as TU Berlin and TU Darmstadt in Germany, TU Eindhoven in the Netherlands, University of Brescia, Politecnico di Torino and Politecnico di Milano in Italy, and around the world including the USA, Canada and China (key institutions include UC Santa Barbara, UC Los Angeles, Columbia University, HP Labs, Hong Kong Polytechnic University, Shanghai Jiao Tong University, and Cybel LLC USA).
- Research at GTO has been recognized internationally, through keynote, invited papers, and talks at major journals, conferences and workshops. Several team members participate in technical program committees at major conferences.

- A state-of-the-art laboratory in optical communication, with unique high-bit-rate transmission platforms maintained by a full-time engineer.
- Interdisciplinary holistic research, covering the main topics in communications from quantum technologies and photonics communications to transmission and networks.
- Attracting outstanding PhD candidates to GTO, by co-coordinating the master track (M2) Optical Networks and Photonic Systems (ROSP), and by teaching on the M2 tracks Quantum, Light, Materials and Nanosciences (QLMN) and Components and Antennas for Telecommunications (CAT).
- Securing research funding from diverse sources: European Commission (ERC, H2020, QSNP), National funding (ANR, FUI), US government, local programs (AMI Compétences et métiers d’avenir QuantEdu etc.) and the private sector (CIFRE programs).

Weaknesses

- The team had only one female professor in the team, and aimed to take practical steps to address the issue of gender parity.

Opportunities

- Collaboration opportunities with international research teams in Europe (Germany, UK, Denmark, Spain, The Netherlands), and around the world (USA, Canada, etc.).
- The team works on a broad range of topics, blending physics with algorithms, which provides opportunities for joint work on interdisciplinary issues.
- New research in quantum technologies may enable the opening up of new funding opportunities, in addition to attracting new students. Collaboration with experts in classical communications and digital signal processing is possible within our team, which to date remains rare around the world.

Threats

- As a result of a growing interest in computer science in recent years, the field of communications and photonics has become less attractive for students. In addition, it is increasingly difficult to engage potential students’ interest in technology such as 5G, whose impact on the environment is as yet not clearly identified.
- Brexit prevented us from renewing as-is the Erasmus Mundus Joint Master Degree SMART-NET (coordinated by Aston University) that previously funded up to 10 students per year in the ROSP master track until 2022. A new EMJMD proposal IntelNetCo is being submitted, coordinated by Politecnico di Torino in Italy.
- In the past few years, optical communication has not been among the top subjects promoted by Télécom Paris.
- It can be difficult to obtain funds in order to maintain and develop the GTO lab.
- Collaboration brings about opportunities, but sometimes also challenges and inefficiencies.

5.2 Attractiveness

5.2.1 Scientific reputation and contributions

The members of the GTO team consistently publish in prestigious journals and conferences with a level of high impact. The collaborative spirit within the team is evident through joint projects with prestigious institutions in France, Europe and worldwide. International recognition of the

team's research is exemplified by the high level of invited papers, and talks at major conferences and workshops. Moreover, the active involvement of several team members in technical program committees of prominent conferences further contributes to the team's global standing and attractiveness.

5.2.2 Staff hosting policy

The team maintains a transparent policy for welcoming new personnel via departmental and personal communication. The policy outlines the procedures for the reception and integration of both junior (PhD and post-doctorate) and senior (EC and C) researchers into the team. The policy clarifies the capacity of the team to host visiting researchers, the available support, and the supervisory framework.

5.2.3 Success in competitive calls for projects

- ANR: N-GREEN, FLIRT, CaLQ, SCODE, SitComOPTICS, PEPR QuanTEdu-France, OPTOPIRAT
- EU: PICs 4 ALL (H2020), FONTE - MSCA ITN (H2020), CIVIQ - FET FLAG (H2020), REAL-Net - MSCA ITN (H2020), COMNFT - ERC (H2020), QSNP (Horizon-CL4-Digital-Emerging-02), CELTIC-NEXT AI-NET
- Institut Carnot
- COMUE UPSay (DigiCosme)

5.2.4 Equipment quality and technological skills

Our optical communication laboratory is equipped with high-performance signal generation and characterization tools, enabling a diverse range of experiments across a number of research areas. These include high-capacity transmission, quantum key distribution, novel optical devices, free space optics, and optical fiber sensing. The laboratory is well-appointed with lasers, amplifiers, detectors, modulators, spectrometers, pattern generators, error detectors, and other essential equipment for near- and mid-infrared data communications. Moreover, we possess advanced instruments such as electrical spectrum analyzers, multiple optical spectrum analyzers with various optical resolutions up to 160 femtometers or 20 MHz, various optical coupling stages for measuring novel photonic chips, real-time oscilloscopes with multiple bandwidths up to 70 GHz, high-capacity arbitrary waveform generators up to 120 Gsamples/s, as well as ultra-low noise tunable lasers. With all these advanced instruments, we have developed and maintained multiple cutting-edge research platforms at the laboratory:

1. a 32 GBaud optical dual-polarization transmission platform used to evaluate the performance of novel modulation formats for optical communication such as nonlinear frequency division multiplexing. The platform was later dedicated to quantum key distribution experiments, specifically for joint continuous-variable (CV) QKD with data transmission, exploiting the ultra-low-phase-noise coherent state of a tunable laser and the DSP of the classical channel;
2. a 64 GBaud optical dual-polarization transmission platform recently mounted to perform data transmission at higher rates, up to 400 Gb/s with state-of-the-art devices and associated DSP algorithms;
3. a versatile optoelectronic device testing platform, capable of characterizing various types of samples from single components, ranging from laser diodes, semiconductor optical amplifiers and waveguides, to photonic integrated circuits with complex functionalities. Wavelength compatibility has also been expanded over the years from O-band (1260-1360 nm)/C-band (1530-1565 nm) only to incorporate both Mid-Wave Infrared (MWIR, 3-5 μm) and Long-Wave Infrared (LWIR, 8-14 μm) bands, that are often used in free-space or satellite-terrestrial communication

- and sensing. This platform enables experimentation with novel photonic devices in a realistic optical system setting, while also facilitating access to fundamental properties down to the material aspect;
4. a home-made optical low coherence-reflectometry (OLCR) platform, capable of facilitating on-chip and in-chip device characterization down to the structural material layers. Applications include optical characterization and metrology such as group delay, chromatic dispersion, birefringence, structural disorder in photonic crystal waveguides, etc.

5.2.5 Synthetic self-assessment

Strengths

- Robust scientific reputation and substantial contributions in top journals in the respective research areas.
- Wide range of topics covered, from the fundamental aspects of the physical layer to optical network architecture and operations.
- Demonstrable success in competitive calls for projects (H2020, ERC, ANR).
- The laboratory is competitive and equipped with top-tier facilities and resources.
- Graduates and post-doctoral researchers have access to excellent employment opportunities both within the industry and academia.

Weaknesses

- Difficulty in staying up-to-date with the latest technological advancements.
- The challenges associated with recruiting PhD candidates and post-doctoral researchers are escalating and becoming increasingly problematic.
- Areas where technological skills may need enhancement.

Opportunities

- Potential for expanding research scope and collaborations.
- Opportunities for securing additional project funding.

Threats

- Risks associated with rapid technological advancements (cost of the equipment).
- International competition in attracting and retaining skilled staff (faculty and research engineers).

5.3 Scientific Production

5.3.1 Qualitative analysis

Area 1: Quantum technologies, devices and communications.

Quantum communication. The use of time-frequency encoding of single photons is under theoretical investigation for quantum communication protocols. In particular, we have developed a quantum encoding that is designed to be robust against noise in quantum communication protocols in addition to the possible error correction strategies [272]. This and further work will be funded by the European project QSNP. New coherent detection strategies for quantum communication and starved (ground to space) quantum communication are currently being designed, funded by

Futur and Rupture IMT PhD funding, and in collaboration with R. Alléaume (QTY, Télécom Paris). In addition, current work is being performed on network planning with coexisting classical and quantum channels via the same physical links, estimating the impact on classical network capacity [602], in collaboration with M. Lourdiane (Télécom SudParis). A future post-doc will be recruited in April 2024 for these activities through funding provided by the European QSNP project.

From an experimental perspective, we are currently building a trusted node QKD network in a joint research project involving Télécom Paris, Orange and the LIP6 research institute, funded by ParisQCI. This work is carried out in collaboration with R. Alléaume (QTY, Télécom Paris), Thomas Riverra (Orange Innovation labs), and Eleni Diamanti (LIP6, Sorbonne Université).

Quantum devices. We are developing Silicon On Insulator (SOI) structures as a promising platform for generating correlated photon pairs. Leveraging silicon micro-electronics technology, it allows large-scale production of integrated photonic chips. Telecom photons offer exciting possibilities for future links between quantum communication nodes or computers. Utilizing the frequency domain for information encoding provides access to a high-dimensional Hilbert space in one spatial mode. We have demonstrated recent advancements in electro-optic quantum information processing of frequency qubits [590] that enable versatile applications, including the implementation of Hadamard gates, frequency ghost imaging, and entanglement swapping. This work was carried out in collaboration with C2N (N. Belabas).

Finally, we have developed a new source of squeezed states of light using quantum dots embedded into semiconductor devices [293], that has great potential for the integration of large frequency ranges working at room temperature. This work has been carried out in collaboration with N. Belabas (C2N, Paris Saclay Université).

Quantum technologies. We are investigating mathematical techniques for the development of phase-space distribution for various quantum systems. In particular, we have investigated phase-space representation in a two-mode quantum field, called SU(1,1) Wigner distribution [274], the Majorana representation of quantum states that is relevant for finding signatures of quantumness [273]. A potential experimental implementation is currently under discussion with a view to an international collaboration.

Quantum key distribution. We performed an experiment demonstrating CV-QKD in coexistence with classical communication. A transmission using PCS-64QAM modulation format on the quantum channel attained a secret key rate of 19.5 Mbps over more than 10km [580].

Area 2: High-speed digital optical fiber transmission

Information-theoretic limits. Optical fiber forms the backbone of communication networks, carrying most of the world's information traffic. The exponential growth of traffic has brought about an escalating pressure on fiber-optic networks. It has been shown that the achievable information rates of wavelength-division multiplexing (WDM) optical transport networks vanish at high powers, in part due to fiber Kerr nonlinearity.

We have made progress with regard to information-theoretic limits in optical fiber, within the ERC project COMNFT funded by the European Commission. We considered a discrete-time continuous-space model of optical fiber described by the split-step Fourier method and showed that its capacity is lower bounded by $(1/2)\log(1 + \text{SNR}) - 1/2$ at high signal-to-noise ratios (SNRs). For a discrete-time discrete-space model of optical fiber, we showed that the asymptotic capacity C as the SNR tends to infinity is doubly-logarithmic, i.e. $C \sim (1/n)\log(\log(\text{SNR})) + c$, where n is the length of the input signal and c is a bounded number. Furthermore, we proved that the capacity-achieving input probability distribution for a zero-dispersion model of optical fiber subject to certain input constraints is discrete in amplitude [275].

In another work, we extended the applicability of nonlinear frequency division multiplexing (NFDm), a transmission scheme based on the nonlinear Fourier transform (NFT), to dual-polarization transmission, thereby doubling the achievable information data rates compared to single-polarization

NFDM in both simulations and experiments [277]. Moreover, we studied an extension of NFDM from signals with vanishing boundary conditions in time with periodic signals, which requires the introduction of a cyclic prefix to prevent inter-symbol interference. In an experiment, we showed that the spectrum of the signal in the periodic NFT is both invariant in distance along the fiber and remains stable, as well as demonstrating data transmission using the periodic NFT for the first time [278].

Digital signal processing using neural networks. The linear transmission effects in optical fiber such as dispersion can be efficiently compensated with DSP. However, the compensation of nonlinear effects is more challenging. With this in mind, we set out to investigate the application of neural networks (NNs) for equalization in optical fiber transmission. This work was carried out as part of three PhD theses within two H2020 MSCA-ITN-EID projects funded by the European Commission: the FONTE project, in collaboration with Aston University, UK, TU Denmark, TU Delft, the Netherlands and Nokia Bell Labs, Germany, and the REAL-NET project, with Aston University, UK, University of Politecnica de Catalunya, Spain and the Infinera Corporation in Germany and Portugal.

In [286], we showed that convolutional recurrent models generally outperform other architectures in nonlinearity mitigation. We explored learned digital back-propagation (LDBP) for equalization in dual-polarization WDM dispersion-managed systems and showed that a low-complexity frequency-domain LDBP substantially outperforms alternative equalizers [260]. To reduce the computational complexity and memory requirements of the NN equalizers, we proposed a companding alpha-blending quantization algorithm that reduces the size of the NN, typically by over 90% [266]. Overall, our findings in these two projects highlight the potential of NNs as effective tools for mitigating nonlinear effects in optical communication.

Shaping for nonlinear interference reduction. While digital signal processing algorithms offer partial mitigation of nonlinear interference (NLI), the inherent nonlinear nature of the fiber, coupled with predominant dispersion effects, continues to challenge the increase of transmission throughputs. Addressing nonlinearity at the information source through signal modulation technology is at the heart of this research area. We work on the design of novel signaling schemes with enhanced tolerance to accumulated non-linear effects in long-haul optical links. These include the design of both probabilistic and geometric-shaped sequences of symbols for various link configurations [282, 284]. In our recent findings, we match and even outperform state-of-the-art signaling schemes by means of a sequence-selection approach through which we transmit data sequences that generate low nonlinear interference when propagating through the optical fiber link [283].

Space-division multiplexing (SDM). We have developed zero-forcing pre-compensation and space-time coding solutions to mitigate core-dependent loss (CDL), and designed active multi-core fiber (MCF) amplifiers that save energy and reduce costs. The work on the design of a cladding-pumped 12-core Er³⁺/Yb³⁺ co-doped fiber (12c-EYDF) amplifier was carried out as part of the multi-partner FUI project EFFLAM.

Area 3: Quantum optoelectronics and nonlinear photonics

The focus of this research area is to produce next-generation quantum optoelectronics that can be directly implemented across the entire range of applications including, but not limited to, optical communications, sensing, photonic computing, defense, and information security. This cross-cutting research intersects a broad spectrum of skills and knowledge from material properties to modeling and simulation of quantum device structures through theoretical work and testing and characterization of the performance of functional devices, with direct insertion into sub-systems and test-bed evaluations. This activity is supported by numerous collaborations with laboratories manufacturing devices, notably the University of Montpellier, ENS Paris, TU Wien (Austria), the University of California Santa Barbara as well as HP Labs (United States).

In collaboration with ENS Paris and the University of Montpellier, we have pioneered the development of high-speed free-space laser communications through the utilization of novel quantum optoelectronics operating within both mid-wave infrared (MWIR)(3-5 μm) and long-wave infrared (LWIR) (8-12 μm)ranges [270]. MWIR and LWIR wavelengths are renowned for their superior transmission performances through inclement atmospheric phenomena, such as fog, clouds and dust. On top of that, the LWIR range provides stealth for the communication signal thanks to random thermal black-body radiation. Indeed, the outdoor environment has a strong emissivity at these wavelengths, and this greatly reduces the probability of adversaries intercepting an LWIR laser signal. On the one hand, using quantum cascade lasers, modulators and detectors, we attained unprecedented data rates of up to 40 Gbps at 9.3 μm [269]. The distance between the emitter and the receiver was 31 meters. This milestone was published in [267] (collaboration with ENS Paris). On the other hand, for the first time, we also pioneered the exploration of intensity noise characteristics in interband cascade lasers and detectors and elucidated their optical transmission capabilities with record bit rates up to 14 Gbps under direct modulation (collaboration with the University of Montpellier and TU Wien) [271].

Furthermore, we play a pivotal role in advancing nonlinear photonics, specifically by considering quantum cascade laser-based communication links using chaos to ensure the security of high-data-rate communications. In this work, we demonstrated the first-ever private data transfer of a 5 Mbit/s 2-level PRBS message by using photonic chaos between two distributed feedback quantum cascade lasers emitting in the thermal infrared window at 9.3 microns. The chaos is obtained by self-external optical feedback on the transmitter side. The message is modulated with a very low-amplitude message and encoded within the chaotic carrier. This private communication system initially demonstrated at 5.6 microns is suitable for data transmission where the concealment of the message is of greater priority than the transmission speed, which is of paramount importance for data transmission in unfavorable or even adverse weather conditions, for example in the case of secure communication between ground vehicles, communication between two satellites, for emergency communication after a natural disaster, or secure and stealthy communication in areas without any infrastructure. Our team was the first to propose this solution which was published in [288]. Still, in the field of nonlinear photonics, we demonstrated the existence of giant pulses in intersubband quantum cascade devices, leading to the development of optical neurons that operate at speeds 10,000 times faster than biological counterparts [289].

Finally, in collaboration with the University of California, Santa Barbara, and HP Labs, we have also significantly advanced the understanding and practical applications of quantum dot lasers [279]. These lasers, known for their compactness, excellent thermal stability, and immunity to large reflections, stand out as the most successful solution for creating photonic integrated circuits with low energy consumption and no need for optical isolation. When directly grown on silicon, quantum dot lasers demonstrate superior four-wave mixing efficiency compared to conventional quantum well devices. This breakthrough opens up possibilities for achieving high-efficiency frequency comb generation on integrated platforms [287]. Additionally, we pioneered the development of integrated quantum dot photonic oscillators, achieving remarkably sharp linewidths down to the Hz level. Recent progress in low-noise pumping circuits for semiconductor lasers has also resulted in the generation of amplitude-squeezed light at room temperature and with several GHz bandwidth. This achievement is of paramount importance for applications such as quantum sensing and quantum light navigation. Overall, our research highlights the potential of quantum dot lasers as clear candidates for integrated technologies on silicon.

Area 4: Optical networks, monitoring and sensing

Machine learning for optical network monitoring. We apply both conventional DSP and machine learning (ML) algorithms to enhance the design and monitoring of optical fiber networks. On the one hand, we study the usage of fast and accurate ML techniques for real-time diagnostics and reconfiguration of the network to limit its unavailability time. For instance, we proposed a

DSP-based method to estimate the power profile of a link without the addition of any hardware to legacy networks [290]. On the other, we explore the potential of ML techniques in designing complex networks such as terrestrial networks with heterogeneous spans or dynamic optical networks with variable signaling rates over the WDM grid [721]. These research initiatives are funded through the CELTIC-NEXT European project AI-NET and CIFRE grants.

Distributed optical fiber sensing. An additional research focus is optical fiber sensing which has gained increasing importance over both dedicated fibers for specific monitoring applications or on a wider scale over dark and lit telecom fibers in order to monitor the telecom infrastructure itself or the infrastructure surrounding the fiber. For instance, we demonstrated the in-band coexistence of a probing channel for distributed acoustic sensing (DAS) with a WDM data transmission without any impact on the quality of transmission over an 80-km fiber span [280]. In another application, we demonstrated independent temperature and strain measurements over optical fibers in a single acquisition using a Brillouin-OTDR probing system [265]. Our team is active in this domain with ongoing collaborations (2 PhD students and 2 post-docs) with industrial partners (Febus, SNCF, Nokia and Thales) through CIFRE grants, an ANR national grant, and an IP Paris Prématuration Grant.

Cross-layer network optimization. An ongoing activity on cross-layer network optimization currently focuses on the simulation of networks that may incorporate all-optical functionalities, especially those that do not readily fit the current layered network paradigm. This is all the more important with the demand for integrating quantum channels, as mentioned above, but should also include other optical functionalities [687, 276]. A greater proportion of optics in the network would allow the leveraging of its high energy efficiency to reduce global energy consumption, which is also a critical need for the coming years [704].

Quantum sensing. In collaboration with MPQ (Paris-Cité Université), we have developed novel strategies in quantum sensing using the time-frequency degree of freedom of entangled single photons for measuring small temporal delay below the attosecond and with sub-shot noise resolution, with our conclusions published in the journal Physical Review Letters [268].

5.3.2 Potential and dissemination strategy

The GTO team regularly disseminates its achievements through various outlets including leading international peer-reviewed journals and conferences ensuring a wider academic reach, as well as special sessions, workshops, and tutorials at international conferences. GTO faculty members also regularly participate in the organization and on the technical committees of a broad range of professional conferences, workshops, or special sessions as part of national and European projects. Quick and efficient dissemination of research is pursued through publication in open-access mode, wherever possible. The publications and associated data (when relevant) are publicly available through *HAL-science ouverte* with free public access.

5.3.3 Scientific integrity, ethics and open science

The team is committed to open science principles and publishing in associated journals for wider accessibility. However, while impact factors may not always apply to open-access journals, the team also prioritizes journals with a strong reputation and influence within our field.

5.3.4 Scientific Highlights

Associate Editors of Journals

- Deputy Editor Optics Express (Optica), since September 2021

- Guest Topical Editor IEEE Photonics Journal, since September 2023
- Associate Editor for the journal of Optical Fiber Technology, Elsevier, since July 2023
- Associate Editor for the Annals of Telecommunications, Springer

Program Chairs of Workshops and conferences

- TPC member of the European Conference on Optical Communications (ECOC), since 2015
- IEEE International Semiconductor Laser Conference, since 2022
- CLEO Europe Conference, since 2021
- Semiconductor Lasers and Laser Dynamics, Photonics Europe, since 2020
- Physics and Simulation of Optoelectronic Devices XXIII, Photonic West, USA, since 2015
- Quantum Sensing and Nanophotonic Devices XII, Photonics West, USA (2015-2018)
- IEEE RAPID Conference, USA (2018)
- Topic Chair of the IEEE Summer Topical Meetings, USA (2019)
- General Chair of the European Workshop on Semiconductor Lasers, France (2021)
- Topic Chair of the IEEE Summer Topical Meetings on Quantum Light Sources & Applications, Mexico (2022)
- Topic Chair of the IEEE Summer Topical Meetings on Quantum & Cryogenic Photonics, Italy (2023)
- Chair of the IEEE French Chapter on Photonics

Organization of workshops, conferences and special issues

- Junior Conference on Optical and Wireless Communications, October 2022 and October 2023
- Spring school Emerging and Future Communication Networks: Technologies, Architectures, and Tools, April 2022
- Workshop on Digital Signal Processing in Optical Fiber Communication October 25, public activity as part of the H2020 MSCA-ITN project REAL-NET, October 2021
- URSI France conference on Nano, Meso, Micro: Science & Innovation for Radio & Photonics, Paris, France, 2022
- International Symposium of Physics and Applications of Laser Dynamics (IS-PALD), November 2019 and November 2023.
- Special issue on Artificial Intelligence in Optical Communications, Optical Fiber Technology, to be published in July 2024
- Seminar Series for the IEEE French Chapter on Photonics

Awards

- ERC Starting Grant COMNFT
- Frédéric Grillot, Achievement Award in Quantum Sensing, Nanoelectronics and Photonics (2024)
- Frédéric Grillot, Optica Fellow (2024)
- Frédéric Grillot, Ampère Medal, Société de l'Électricité, de l'Électronique et des Technologies de l'Information et de la Communication (2023)
- Frédéric Grillot, IEEE Photonics Society Distinguished Lecturer Award (2022)
- Frédéric Grillot, Innovation Award – The University of New Mexico, (2020)

- Frédéric Grillot, SPIE Fellow, The International Society for Optical Engineering (2019)
- Sterenn Guerrier, IP Paris best thesis award, 2023
- Bozhang Dong, IP Paris best thesis award, 2022
- Bozhang Dong, Springer Nature Outstanding PhD Thesis, 2023
- Olivier Spitz, Prix de thèse DGA, 2021
- Olivier Spitz, Springer Nature Outstanding PhD Thesis, 2020
- Jianan Duan, 2ème prix de thèse de la fondation Mines-Télécom, 2020
- Louise Jumpertz, Prix de thèse DGA, 2018;
- Louise Jumpertz, Springer Nature Outstanding PhD Thesis, 2017

Research contracts

- H2020 MSCA ITN-EID Project FONTE, European Commission
- H2020 MSCA ITN-EID Project REAL-NET, European Commission
- H2020 FETFLAG CiViQ, European Commission
- H2020, Projet PICs4All, European Commission
- ERC Starting Grant COMNFT, European Commission
- European Quantum Flagship, QSNP
- CINT Los Alamos, USA
- Air Force Office of Scientific Research (AFSOR), USA
- ANR N-GREEN, FLIRT, SCODE, SitComOPTICS, PEPR QuanTEdu-France, OPTOPIRAT
- FUI EFFLAM project, FUI-AAP21, funded by the Research Network of the State of Brittany
- Franco-German Program PhC Procop
- Direction Générale de L’Armement
- Hewlett-Packard Enterprise
- CELTIC-NEXT AI-NET Antillas project, BPI France
- IP Paris prematuration grant for SAFER project
- Huawei Technologies France
- SNCF, Orange, Ariane Group
- Observatoire de Paris/LESIA
- DIGITEO-COCCINELLE, DIGITEO-MOVIET (FCS UPSay)
- Institut Carnot, Prematurations DODECANESE & WITHIN

Sabbatical stays

- Frédéric Grillot, Visiting Professor, Politecnico di Milano, Italy, September 1, 2023 – December 31, 2023 (4 months)
- Frédéric Grillot, Visiting Professor, University of Santa Barbara, USA, July 22, 2023 – August 23, 2023 (1 month)
- Frédéric Grillot, Visiting Professor, University of California Los Angeles, USA, April 1, 2017 and December 31, 2017 (2 × both for 3 months)
- Yves Jaouen, Cybel (a photonics company), Bethlehem, Pennsylvania, USA, February 15, 2022 – June 13, 2022 (3 months)

- Yves Jaouen, Shanghai Jiao Tong University, Shanghai, China, March 1, 2024 - April 27, 2024 (2 months)
- Yves Jaouen, Beijing Institute of Technology, Beijing, China, April 29, 2024 - June 29, 2024 (2 months)

5.3.5 Synthetic self-assessment

Strengths The collaborations with both the Quantum Information Processing and Communication Saclay (QURIOSITY) teams and the Digital Communications (ComNum) team at Télécom Paris in addition to those with international research teams strengthen the position of GTO and foster interdisciplinary research opportunities.

Weaknesses Strengthening efforts to increase the number of patents and intellectual property assets to enhance our competitive position in technology transfer to industry. Enhancing efficiency in open science publishing.

Opportunities Our ongoing collaboration with international research teams paves the way for more diversified and impactful research initiatives. Partnerships with industry players are a clear asset and can lead to concrete implementations of our research, as well as to increased opportunities for potential funding.

Threats The rapid pace of technological change in optical communications can lead to certain growing difficulties due to the rapid obsolescence of certain equipment if it is not continually upgraded. In addition, current external factors such as geopolitical events and the recent Covid-19 pandemic may have a direct impact on our international collaborations and research activities.

5.4 Contribution of Research Activities to Society

5.4.1 Socioeconomic partnerships and interactions

Collaborating with industry and relevant stakeholders, our team is actively fostering partnerships to ensure that our research aligns with socioeconomic needs. By engaging in dialogue and collaboration, we aim to create a seamless transition of our research outcomes into real-world applications, contributing directly to economic growth and technological advancements.

5.4.2 Research valorization and transfer

Our commitment to research valorization involves actively seeking avenues for potential technology transfer. Through collaboration with industrial partners, we aim to transform our research findings into practical solutions, fostering innovation and contributing to economic development.

5.4.3 Science popularization

Thanks to the support of QuanTEdu-France, our team is committed to implementing concrete training initiatives in the field of quantum technologies, spanning all stages of education from pre-university to doctoral training. These training programs will be delivered as part of both initial and ongoing education initiatives. The goal is to create jobs in the quantum field by 2030. Overall, our dedication to science popularization extends beyond conventional methods. We leverage various platforms, including social media, workshops, and community outreach programs, to disseminate knowledge and create awareness about the work deployed within the team. This approach not only enhances public understanding but also promotes the societal relevance of our research. Furthermore, several times, we have hosted high-school students and introduced them to our research and teaching activities to foster their interest in science and engineering.

5.4.4 Synthetic self-assessment

Strengths We are very proactive in setting up collaborations and partnerships with industry. Our ongoing efforts translate research into practical applications. We are committed to promoting innovative science popularization strategies for wider dissemination. The portfolio of the team for 2018-2023 amounted to 3.5 million€.

Weaknesses There might be certain potential gaps in external visibility, thus requiring stronger communication strategies. We should also consider taking opportunities to further optimize the dissemination of our research findings through diverse channels.

Opportunities The clear growing demand for quantum technologies presents opportunities for a more extensive range of collaborations and enhancing attractiveness to students. Our strategic partnerships can further amplify the impact of our research outcomes on a much broader scale. Furthermore, the intrinsic energy efficiency of optical communications should make it a highly-sought after topic, provided that we can specifically contribute to reducing global energy consumption, and thus avoid rebound effects.

Threats The intensifying competition in the quantum technology sector may require greater visibility. In addition, we will have to ensure that the societal value of our initiatives is adequately recognized in a competitive landscape.

Chapter 6

Self-assessment of LabSoC team

6.1 Profile, Resources and Organization

6.1.1 Scientific objectives

The LabSoC team is dedicated to developing innovative methodologies, techniques, and tools that enhance the **analysis and design of embedded systems**. Our focus is on improving these systems in terms of safety, cybersecurity, and performance, with a particular emphasis on exploring the design space of these systems. Our research is driven by the recognition of a significant gap in the field: the need for a **holistic approach to address the intricate interplay between safety, security, and performance**. We target a broad spectrum of applications, prioritizing systems that are both safety-critical and interconnected. In an era where connectivity can introduce new vulnerabilities, the intersection of safety and cybersecurity is crucial. Our work is based on the premise that breaches in security can lead to unsafe behaviors in these critical systems, thus creating the need for integrated and resilient design strategies. Finally, our main scientific focus areas are:

- Definition of model-based languages and verification techniques for addressing new characteristics and needs (e.g. cybersecurity) of embedded systems.
- Definition of new verification techniques able to handle the complexity of embedded systems
- Adapted tools for handling the analysis and design of embedded systems

To address these challenges, LabSoC conducts multidisciplinary research that integrates principles from model-based practices, formal techniques and verification, and system analysis. We develop techniques for the design space of embedded systems to better identify and mitigate potential vulnerabilities early in the development cycle (at system level). Through a combination of innovative theoretical modeling (e.g. modeling languages, agile verification techniques) and practical experimentation (applications-guided, platform-guided), we define techniques and tools (e.g. TTool) intended to guide the design of systems that are more resilient to cyber threats.

The threats we consider range from classical probing of networks and message injections to side-channel attacks, i.e. monitoring time and diverse side signals emitted by systems while they execute. While we mostly focus on how to efficiently integrate safety and security mechanisms together in order to fulfill safety and security requirements, we are also interested in designing new support for security threats. At present, the contributions we develop, whether hardware, software, or both, also support performance and safety requirements.

The application areas we consider are:

- Transportation systems (e.g. automotive systems, drone systems)
- Industrial systems (using for instance the IT'M factory platform)
- Telecommunication systems (e.g. 5G systems)

6.1.2 Resources

A distinctive feature of the LabSoC team is that its permanent researchers come from different research areas, including model-based design, formal description techniques and electronics, which are closely linked to the design of embedded systems. Moreover, this team is involved in a number of collaborations, either with other teams of the LTCI (including SSH), or with external academic partners (Inria, ISAE, LIP6) with whom they regularly publish articles and research findings, as well as a number of industrial contacts, as demonstrated by several bilateral contracts.

- *Human resources*

- Team leader: Ludovic Apvrille (Full Professor).
- Faculty between 2018 and 2023: Renaud Pacalet (Full Professor), Sophie Coudert (Associate Professor), Ludovic Apvrille (Full Professor), Rabéa Ameur-Boulifa (Associate Professor, HDR since 2023), Tullio Tanzi (Full Professor, then Emeritus Professor since beginning of 2023).

- *Platform*

The team has initiated and drives the development of the TTool toolkit. This toolkit serves as a demonstrator for many of our research contributions in the field of system modeling and verification.

- *Financial resources*

The team benefits from many types of research funding from both national and international sources:

- CIFRE contracts from ANRT: Alcatel Lucent (2 PhDs), Virtual open systems (1 PhD), Engie (1 PhD), Renault software labs (1 PhD)
- PhDs in collaboration with the SSH team: "Paris region PhD" contract and Ekinops (1 PhD), the "ARSENE" ANR PEPR Cybersecurity project (1 PhD), Thales and the "Innovation Défense" agency (1 PhD)
- Industrial chair: C3S (1 PhD, 1 post-doctorate)
- Intercarnot project: TWIST (1 post-doctorate)
- PEPR projects: PERP-5G (since January 2023)
- Horizon2020: SPARTA (1 post-doctorate), AQUAS (1 PhD), NETCOM (1 PhD)
- Bilateral project: Nokia Bell Labs (3 PhDs, 2 research engineers)
- Grant: Huawei (1 post-doctorate)

6.1.3 Human resources management, safety, environment, ethical protocols, data and scientific heritage protection

The team meetings are weekly based, with monthly scientific seminars. Some extra meetings take place for specific events (recruitment, brainstorming).

The team is sensitive to gender equality. Currently, the field of computer science and electrical engineering does not attract many women. Having a better gender balance would open up more opportunities for young female students. It should be noted that Rabéa Ameur-Boulifa received her HDR in 2023.

In accordance with laboratory policy, the team is sensitive to sustainable development. It notably limits travel whenever a virtual meeting is possible. The same applies to conferences, where either local or virtual events are preferred, or the number of physical attendees is limited to one researcher.

6.1.4 Synthetic self-assessment

The team's main research focus lies in the analysis and design of embedded systems. Embedded systems are at the intersection of diverse disciplines, including computer science and electrical engineering. The application areas of our research are also highly diverse, ranging from highly critical systems (e.g. automotive systems) to systems with a high availability (e.g. telecommunication systems). The team has the required expertise to lead top research in the aforementioned technologies and application areas, with a team boasting over 20 years of experience.

Strengths One of the team's main strengths is its multidisciplinary expertise, which enables researchers to contribute competitive research in the field of embedded systems. This expertise includes computer science, digital electronics, safety and cybersecurity.

Weaknesses As with many other research laboratories, we experience difficulties in attracting outstanding PhD candidates. We are working on this by hiring more interns and taking advantage of additional opportunities such as IP Paris PhD tracks. In addition, we compensate our lack of young permanent researchers with post-doctorates and research engineers.

Opportunities The team has progressively introduced AI both in their research (e.g. model-based engineering) and tools (TTool), which already offers new opportunities (e.g. calls to participate in European projects).

Threats Several of the team's researchers will retire in the next 10 years.

6.2 Attractiveness

The team maintains a close relationship with academic and industrial partners, either as part of publicly funded projects, or via significant bilateral funding, thus offering us a way to recruit a number of PhD candidates, post-doctorates and research engineers. Most positions we offer are linked to these industrial contracts, but we also conduct more fundamental research, either from a project's margins or as part of publicly funded fundamental research.

6.2.1 Scientific reputation and contributions

Our work on the design of embedded systems has been long acknowledged, as proved by our number of publication references, bilateral contracts and numerous invitations to participate in European and national calls for projects.

Another success of the LabSoC team is the free and open-source tool "TTool" created and mostly developed by LabSoC itself. This tool offers modeling and verification features adapted to the analysis and design of embedded systems. It is used as part of teaching activities on our courses, but also at other institutions such as ISAE-SUPAERO. It is also the main demonstrator of our research in which most of our contributions are integrated. For instance, as part of the H2020 AQUAs project, it has been used for intermediate and final demonstrations. The tool has also proved attractive to many of our industrial partners. Last but not least, many LabSoC papers demonstrate the value of their contribution using TTool, including [297, 332, 305, 345, 338, 313, 303, 344, 322, 331, 343, 316, 317, 312, 308, 341, 342, 908, 315, 330, 299, 340, 318, 319, 304, 307, 302, 311, 328, 326, 306, 321, 320, 310, 309, 327, 334, 333, 298, 323, 314, 300, 324, 346].

6.2.2 Staff hosting policy

Apart from its national and international academic and industrial relations, the team directly hires interns, PhD candidates, post-doctorates and research engineers using contract funding. All prospective candidates go through competitive and technical tests, including problem solving and paper reviews.

6.2.3 Success in competitive calls for projects

During the evaluation period, the LabSoC team has been involved in many different projects:

- Bilateral project, i.e. projects directly set up by LabSoC. These include 5 CIFRE projects, one large-scale project directly funded by Nokia Bell Labs (financing 3 PhDs and a research engineer), and a grant from Huawei.
- Publicly funded projects. These include, for instance, Netcom, AQUAS and Sparta CAPA (European project), PERP-5G (ANR) and Twist (Intercarnot).

With regards to its number of permanent researchers (5), LabSoC is especially successful in setting up or participating in competitive projects.

6.2.4 Equipment quality and technological skills

The LabSoC team possesses wide-ranging expertise in the development of platforms to support their research. This includes:

- TTool. A tool to model and verify embedded systems. It includes 700,000 lines of code, demonstrating both the ability of the team to develop concepts as well as introduce them in large-scale software
- Arcturius. An automated rover to host equipment we design. While still a prototype, it nevertheless demonstrates the ability of the team to develop platforms capable of hosting embedded systems designed by the team.

6.2.5 Synthetic self-assessment

Strengths A significant number of projects in collaboration with recognized research centers (e.g. Nokia Bell Labs), and participation in many publicly funded projects. Recognized platform (TTool)

Weaknesses Attracting outstanding students is challenging.

Opportunities Entering new scientific circles (academic, industrial) as part of new research activities, in particular around AI.

Threats Maintenance of tools is costly for the team (but mandatory for technology demonstration). Recruiting a long-term research engineer would certainly help.

6.3 Scientific Production

6.3.1 Qualitative analysis

The following analysis demonstrate our ability to publish cutting-edge contributions at high-rank conferences, as well as making contributions both in our core research areas (modeling and formal verification of embedded systems) and via the platforms used for supporting our research activities (TTool, Arcturius).

During the period 2018-2023, the LabSoC team produced 16 journal papers, 57 articles in proceedings, 9 book chapters, 2 magazines, 1 keynote, 1 habilitation thesis and 11 completed PhD defenses, including co-supervisions¹ (with Inria and Eurecom).

Conf.	Journals	Chapters	Mag.	Keynotes	Best Paper Award	HDR	Defended PhDs
57	16	9	2	1	1	1	11

TABLE 6.1: Key metrics

¹source: theses.fr

Publications

Most of our publications are concentrated on our core research areas: models, their semantics, and (formal) verification. Here, we highlight several examples of our successful research endeavors, which are substantiated by publications at leading conferences and journals within our field.

- **Enhancing graphical languages with formal semantics.** While graphical languages such as UML/SysML have firstly been defined with safety in mind, we have enhanced SysML with a formally defined SysML-to-Proverif transformation, in order to provide SysML with (formal) security proof capabilities. In particular, [296] provides a formal definition of this transformation, which can now be used for general-purpose systems. A similar transformation have also been defined for platform-based design [327] (**Best paper award**). We have also investigated new models and model transformations for digital-analog systems, thus leading to the definition of a unique environment that can handle computational models that significantly differ [313, 314]: this work has been carried out in collaboration with LIP6.
- **Safety-security interrelations.** We have investigated innovative methods for analyzing and detecting negative interrelations between safety and security mechanisms when designing embedded systems. For instance, within the development framework of the automotive industry, with verification as the primary objective, we have defined a new formalization method to specify requirements [339] and to handle their specific safety/security reinforcement and opposition [299]. Similarly, in program vulnerability analysis, we have formalized specific aspects of execution environments that could impact program security [325]. We have also defined a new methods, called W-Sec, dedicated to the co-investigation of safety and security during a system development cycle [333]. Finally, to analyze vulnerability directly from programs, we have abstracted and formalized execution environments that could impact program security [325].
- **Model mutation.** [334] showcases our scientific contribution in the field of modeling and verification, particularly when safety/security/performance aspects are at stake [300]. The formal definitions allow the subsequent definition of model mutations, that are then used to update the security mechanisms under evaluation. AMULET is now part of TTool. The use case of the paper, provided by Mines Saint-Etienne and taken from the ITM'Factory system, demonstrates the ability of our mutation language to efficiently assist engineers to update their model when new attacks have been discovered.
- **Models and analysis techniques applied in specific area.** In the context of our collaboration with Nokia Bell Labs, we addressed the problem of the dynamic scheduling of tasks on FPGA resources in the cloud and data center environments. These cloud architectures are particularly useful for accelerating computation-intensive tasks, for instance those found in signal processing. A fast scheduling algorithm named Slot was proposed and evaluated. [329] Slot outperforms the state of the art. With its near optimal scheduling and fast run times, it is a promising solution for the effective management of reconfigurable resources in the cloud.
- **Exploring modeling and verification techniques.** Our team is actively exploring new formalisms to facilitate the modeling and verification of complex and embedded systems. These formalisms, in the form of symbolic models enabling hierarchical representation of systems and their interactions, can serve as the foundation for the development of innovative compositional [295] and incremental verification techniques [294, 300, 298].

Tooling

The teams is closely involved in the development of two platforms supporting our research activities.

- **TTool**², an open-source UML/SysML toolkit developed by LabSoC since 2004, comprises over 700,000 lines of code and serves as a key platform for our research in modeling and verification.

²<https://ttool.telecom-paris.fr>

During the evaluation period, It has been upgraded by means of security-focused, formally verified model transformations [296], and with model mutation capabilities [334]. New formal verification techniques have also been defined and implemented in TTool, such as incrementality in verification [297], and fine-grained analysis of verification results [345]. Additionally, TTool introduces initial AI-based modeling assistance features, which we plan to enhance and expand in the coming years, going much further than the latest advancements in the field. Automated integration of safety and security patterns is also a promising contribution we are working on.

- **Arcturius** [336] is a rover designed to bolster our teaching and research endeavors. Although currently in development, the rover’s advanced capabilities, such as handling challenging terrains and offering an easy payload configuration, make it a suitable platform for validating the development methodologies we propose in our research [335]. Furthermore, it serves as a practical testbed for the equipment we develop, illustrating the applicability and effectiveness of our methods in real-world scenarios.

6.3.2 Potential and dissemination strategy

LabSoC’s main research area is shared by all team members: modeling and verification of embedded systems. Many publications are produced with at least two permanent LabSoC staff members. This includes in particular recent work on requirement engineering, model mutations, and new verification techniques (incremental verification).

Dissemination at LabSoC is targeted to all the established channels: scientific conferences and journals, websites (such as the TTool website), public GitLabs, magazines (such as MISC and Programmez!), videos (e.g. available on the TTool website), involvement in GDRs (co-leading and animating the YODA GT as part of GDR-GPL) and conference organization (such as Ph0wn).

6.3.3 Scientific integrity, ethics and open science

LabSoC’s general policy is to release whenever possible its contributions as open science. This includes project results, publications (including HAL), and software (e.g. TTool). Furthermore, LabSoC publicly releases material to reproduce research results whenever it is practicable, using for instance dedicated GitLab repositories.

6.3.4 Synthetic self-assessment

Strengths A high level of publications and defended PhDs considering the pandemic situation.

Weaknesses Attracting highly skilled PhD students and post-doctorates is challenging, thus impacting our scientific production and our ability to produce qualitative publications and deliverables.

Opportunities We are now involved in IP Paris master’s programs and Ph.D. tracks, and we intend to attract more internship students.

Threats The way laboratories publish is rapidly evolving: open science journals, etc. LabSoC must be attentive to this trend and adapt its publication strategy accordingly.

6.4 Contribution of Research Activities to Society

6.4.1 Socioeconomic partnerships and interactions

LabSoC is deeply involved in direct partnerships with the economic world, mainly in areas related to telecommunication and embedded systems. For the evaluation period, we can for instance mention partnerships with Nokia Bell Labs and Huawei on the telecommunication side, and Renault Software Labs and VEDECOM for embedded systems. Chaire C3S (Renault, Wavestone, Nokia, Thalès) was also an important project for setting up links with various partners. For example, we are currently negotiating PhDs with Renault, and have written European project proposals

with Thalès. Project AQUAS (H2020 project) was also important in setting up relations with Thales Alenia Space (use case with TTool) and Clearsy (several use cases, and they now make presentations in our lectures). Project SPARTA CAPE (H2020) was a catalyzer for setting up a collaboration with Fortiss, and later on with Huawei.

These direct collaborations have a major impact on LabSoC, both from a financial point of view (financing of PhDs and engineers), and from a research applicability perspective, since these direct interactions usually correspond to the application of our fundamental research to more practical industrial perspectives. Some of these collaborations are mostly short-term opportunities, meant to set up promising research, or elaborating use cases conducive to improving our tools and demos. Other collaborations are mostly long-term (Renault, Nokia, Thalès, Fortiss, LIP6, Supaero) and offer the opportunity to jointly address scientific challenges, with top publications, for instance [329] (Nokia) or [339] (Renault).

6.4.2 Research valorization and transfer

The LabSoC team pursues a range of valorization and transfer strategies. Apart from publications, LabSoC is involved in:

- Several bilateral collaborations that have led to co-improvements of TTool, and the use of TTool and our research outcomes by industrial partners
- Several European projects (AQUAS, SPARTA), where TTool was one of the most widely used (and improved) toolkits
- LabSoC also collaborates with several academic institutions, such as ISAE-SUPAERO, LIP6, and ITA (Brazil), that are both contributors to and users of TTool (for both teaching and research activities). TTool is not just a technological showcase; it is also a means of technology transfer and emulation shared with our partners.

6.4.3 Science popularization

LabSoC participates in two actions:

1. Publication in magazines available to the general public. For instance: F. Lugou, L. Aprville, "Analyse d'un problème posé par Intel SGX : la communication sécurisée entre une enclave et un périphérique" (In English "Analysis of an Issue Raised by Intel SGX: Secure Communication between an Enclave and a Peripheral"), MISC Multi-System and Internet Cookbook, MISC n. 108, Nov-Dec 2018. (in French) [328]
2. The participation to "Forum des prépas" in high schools to present both our teaching and research activities to students between 14-20 years old.

6.4.4 Synthetic self-assessment

Strengths Platforms help us to valorize our work, they make it possible to develop partnerships. This is definitely something we should continue developing.

Weaknesses Platforms are mostly technological showcases, no industrial transfers have been made (but this is not our objective).

Opportunities Deep bilateral collaborations could help us train our platforms on concrete product development. We do intend to develop this as part of the new ICMS chair, in particular with Renault. We have an additional opportunity with the BPI project we have proposed with Prove&Run.

Threats Maintenance of tools is costly for the team. Recruiting support engineers would enable better valorization.

Chapter 7

Self-assessment of RFM² team

7.1 Profile, Resources and Organization

7.1.1 Scientific objectives

The RFM² team focuses on connections and interactions between humans and machines, which requires energy-efficient wireless systems, either mobile or embedded, alongside sensing mechanisms capable of adapting to their environment. It is therefore necessary to provide optimal connectivity with respect to cost, energy efficiency, performance, and flexibility in any type of environment and to reduce exposure below the legal limits. In agreement with the strategic areas defined at the last evaluation, the field of competencies of the RFM² (Radio Frequency, Microwaves, and Millimeter Waves) team has grown during the last six years. This evolution is primarily linked to three events. The first is the development of a new theme around energy harvesting and far-field wireless power transfer (following the recruitment of K. Niotaki). The second is the reinforcement of non-linear circuit activity on the characterization of non-linear power components at millimeter wave frequencies (primarily supported by R. Mohellebi). The last event is the strengthening of the activities of the C2M Chair (Characterization, Modeling and Mastering of EMF Exposure) linked to questions and health concerns induced by the deployment of 5G.

RFM²'s expertise focuses on three main areas. The first is the design of components and subsystems for radio links in communicating systems for emerging digital applications (beyond-5G, IoT, satellites, localization, reliable and secured massive communications, etc.). The performance of these components and systems is then enhanced thanks to the innovative characterization methods in microwave and millimeter wave domains being developed by the team. Modeling is the third area requiring a mastery of the knowledge of components and subsystems to determine interactions between waves and humans. The optimization of technologies and networks for telecommunications requires exceptional knowledge of systems and subsystems and requires multi-domain skills. The ability of RFM² to work simultaneously on antenna-circuit co-design and integration in addition to joint antenna-channel modeling is essential to meet the needs of diverse and complex architectures.

The two main research areas of the RFM² team focus on the optimization of telecommunication systems by:

- Pushing RF technologies to the limits through innovations in physics and technology: from low-cost/low-speed to high-performance/broadband components and systems for humans, objects and connected machines.
- Pushing the optimization of "5G and beyond" technologies by improving indoor localization systems, developing novel methodologies and surrogate models for antennas and propagation by taking into account the nearby environment and analyzing human-wave interactions.

7.1.2 Resources

- *Human resources:*

Team leader: Jean-Christophe Cousin (Associate Professor, team leader until October 2023), Xavier Begaud (Professor, team leader since November 2023).

Faculty: Eric Bergeault (Professor, 20%), Antoine Khy (Research Engineer), Anne Claire Lepage (Associate Professor), Reda Mohellebi (Research Engineer, 25% since April 2022), Kyriaki Niotaki (Associate Professor since November 2020), Christophe Roblin (HDR, Associate Professor), Alain Sibille (Professor until September 2021, Professor Emeritus since October 2021), Joe Wiart (HDR, Head of Chair C2M).

Post-docs: Xi Cheng, Zain Haider, Sang Woo Kang, Zicheng Liu, Jiang Liu, Pedro Mendes Ruiz, Olivier Rance, Shanshan Wang, Yarui Zhang, Ce Zheng.

PhD Students: Maarouf Al Hajj (defense 2022), Mohamed Aliouane, Nour Awarkeh (defense 2019), Soumaya Azzi (defense 2020), Juan Bucheli Garcia (defense 2020), Amirreza Chobineh (defense 2020), Cheikh Diakhate (defense 2019), Jinxin Du (defense 2018), Bader Mustafa Fetouri (defense 2021), Rafael Gonçalves Licursi de Mello (defense 2022), Seyedfaraz Jafari (defense 2023), Biruk Mulugeta, Thi Dao Pham (defense 2019), Raziye Sharifi, Théo Spillebout, Tien Tu Vo (defense 2019), Yibo Wang, Badre Youssef (defense 2023).

Engineers: Wassim Ben Chikha, Taghrid Mazloum, Reda Mohellebi (until March 2022), Sriku-mar Sandeep.

- *Platforms:* The team has developed and/or exploited the following platforms:

- Non-linear on-wafer characterization of millimeter wave components
- Microwaves and millimeter wave anechoic chambers
- StarLab for near field measurements

- *Funding:* We diversify our funding sources, both national and international, as well as academic or industrial (e.g. CIFRE funding with Orange Labs, Thales AVS and LNE), to enable us to carry out research that covers both fundamental and applied aspects and also to maintain a sufficient budget to keep up to date with costly instrumentation.

Type of contracts	European	ANR, ANSES, BPI, AID	C2M Chair	Bilateral	CIFRE	Miscellaneous
Budget	€1.1M	€1.8M	€2.7M	€0.211M	4 grants	€0.23M

7.1.3 Human resources management, safety, environment, ethical protocols, data and scientific heritage protection

Responsibilities are shared within the RFM² team. Almost all team members have a specific administrative and/or collective responsibility in addition to their teaching and research duties. The aim is to involve everyone in the life of the team, to train new team members, and to improve the team's scientific reputation.

Team meetings are held every month. Other meetings take place for specific events, for instance, the recruitment of a new faculty member, creating and managing teaching activities, or preparing future investments.

The team is sensitive to gender equality and strives to achieve a better gender balance in terms of faculty members, students, and post-docs.

The RFM² team is aware of sustainable development issues and limits travel when a virtual meeting is possible and maintains a policy of one single international trip per researcher, per year.

7.1.4 Synthetic self-assessment

Strengths The team consists of researchers with a unique set of skills and state-of-the-art testing facilities up to millimeter wave frequencies. Furthermore, the complementary skills of the RFM²

team enable cutting-edge fundamental upstream and applied research on circuits and antenna designs, MMIC and antenna characterization, wave propagation, and wave/human interactions models up to 170 GHz.

Weaknesses The team covers a wide range of skills and has multiple areas of expertise, but encounters certain difficulties in responding to certain types of calls for projects on highly specialized subjects, for which a "critical mass" team is required.

Opportunities The recruitment of a faculty member will ensure the long-term future of the C2M Chair within the RFM² team. The upcoming preparation of new HDRs will increase the number of students to be supervised.

Threats The ongoing changes in organizational structures are extremely time-consuming and have a direct impact on the scientific production of the team.

7.2 Attractiveness

7.2.1 Scientific reputation and contributions

- *International recognition:*

- K. Niotaki: Vice-Chair of the IEEE MTT-S Technical Committee (TC-26) on 'RFID, Wireless sensors and IoT' for the term 2022-2023 (2 years).
- J. Wiart: Chair of the URSI commission K for the term 2014-2021. Chair of European Standardization CENELEC TC 106x.
- A. Sibille: TPC Chair of URSI GASS 2021 (Rome, Italy).

- *National recognition:*

- A. Sibille: General secretary of URSI-France (since 2012).
- A.C. Lepage: Co-Chair of the think-tank group on "New Antenna Concept" of GDR-Ondes (CNRS).
- J. Wiart: Project leader of Euramet MEWS (2022) and SRT (2021), Chairman of AFNOR UF 106, Chairman of the Steering Committee of the Paris Wave Observatory.

- *Specials sessions* : JS URSI 5G 2020, iWAT2020, IEEE CAMA 2021, URSI AT-RASC 2022, Meta 2023, URSI GASS 2023, URSI AT RASC.

- *Editorial activities* :

- X. Begaud, Senior Topical Editor at AEM, <https://aemjournal.org/index.php/AEM>.
- C. Roblin, Area Editor (Transmission and communication technologies) of Annals of Telecommunications, <https://link.springer.com/journal/12243/editors> (Springer).
- J. Wiart, Guest Editor of Special Issue Networks of the future: 5G and beyond, Comptes Rendus Physique Vol. 22, 2021, <https://doi.org/10.5802/crphys.73>.
- A.C Lepage and X. Begaud, Special Issue Editors of Metamaterial and Metasurface Design for Microwave Applications, Materials.
- J. Wiart, Guest Editor of Special Issue Electromagnetic fields (EMF) exposure, Annals of Telecommunications, Vol. 74, pp. 1–3, 2019 (Springer), <https://doi.org/10.1007/s12243-018-0698-4>.

- *Invited speakers:*

- A. Sibille: RINEM 2018 (Cagliari, Italy) [645].
- X. Begaud: Marina Forum on Metantennas 2022 (Singapore) [608].

- *Invited talks:*

- O. Rance: Meta 2018 [643]; A.C. Lepage: IEEE CAMA 2021 [631], Meta 2023 [630]; K. Niotaki: URSI GASS 2021 (Rome, Italy) [635]; X. Begaud: iWAT 2022 (Dublin, Ireland) [609], AES 2022 (Marrakesh, Morocco) [610]; R. Licursi: Meta 2023 [624].

- *International collaboration:*

- C. Roblin has been developing a collaboration with the Sino-European School of Technology, Shanghai University, China, since 2018 [618, 619, 628].

- *Awards :*

- K. Niotaki: URSI Young Scientist Award, 2021.

Most RFM² team members are involved in TPCs or the organization of international (AES, EuCAP, EuMW, Meta, PIMRC), and national (JNM, URSI) flagship conferences in the field. They also contribute as reviewers for international scientific journals (IEEE Access|AWPL|IM|MTT|TAP, IET MAP, Materials, Nanomaterials, . . .) and conferences (EuCAP, EuMW, IEEE CAMA|ISAP|iWAT, PIMRC, . . .).

7.2.2 Staff hosting policy

The 2018-2023 period was complicated in terms of maintaining the policy of inviting professors on sabbatical leave. We had to deal with the move to new premises as well as the various restrictions as a result of the Covid-19 pandemic. As the team's skills rely heavily on its characterization platforms, operations were slowed down considerably. However, the team managed to maintain a reception policy during this period: Professor Leandro Juan-Llácer (from UPCT, Universidad Politécnica de Cartagena, Spain) was able to carry out measurements to characterize propagation channels for his work.

In addition, we also carried out a recruitment campaign for a lecturer position in the field of RF and millimeter wave circuit and system design, thus covering the team's main skills in the field of design of radio front ends. The outcome of this campaign enabled the international recruitment of Ms. Kyriaki Niotaki.

7.2.3 Success in competitive calls for projects

The team is active in various calls for projects both nationally and internationally. In this context, we appear in the following European project consortiums:

- SEAWAVE (<https://seawave-project.eu/>): The aims are the scientific-based exposure and risk assessment of RF and mm-wave systems from children to the elderly (5G & Beyond) (2022-2025).
- MEWS 21NRM03 (<https://projects.lne.eu/jrp-mews/>) for metrology (2022-2025).
- GOLIAT (<https://projectgoliat.eu/>): GOLIAT aims to monitor exposure to radiofrequency electromagnetic fields (RF-EMF), particularly from 5G, and to provide novel insights into its potential causal health effects (2022-2027).

In national calls for projects, we are active in the different types of initiatives listed below:

- DIOD (FUI 24): Design and measurement of the antenna array (96 radiating elements) of a Radar. Partners: When-AB, Thales, CentraleSupélec, Bowen ERTE-ETSA (2018-2022).
- EXPLORA (ANSES): Exposure induced by mobile phones. We lead this project and CEA-Leti and EXEM are the partners (2019-2023).
- Beyond 5G (<https://beyond5g.wp.imt.fr/>): supported by BPI (2022-2024).
- OPALE (AID): Shutters and Reconfigurable Radiating Panels. We are responsible for the study of self-complementary antenna arrays. Partners: IETR, Xlim, CEA-Leti, ICMCB (2023-2026).
- Networks of the Future PEPR (Priority Research Equipment Program): The team contributes to NF-PERSEUS and NF-JEN projects (<https://pepr-futurenetworks.fr/>) (2023-).

7.2.4 Equipment quality and technological skills

One source of added value provided by the RFM² team is its technical competencies covering RF and millimeter wave characterization. In this way, the main highlighted platforms of the team are the 2 anechoic chambers facilitating antenna characterization up to 170 GHz, and a probe station dedicated to the source pull/load pull non-linear characterization of millimeter wave (40 - 60 GHz) power amplifiers. As part of the nonlinear characterization of GaN components or power amplifiers in millimeter wave frequencies, an NDA was signed with the III-V Lab to carry out nonlinear source pull/load pull characterization of power amplifiers in the 40 - 60 GHz range. This platform, unique in the Saclay and Palaiseau research environment, should make us a key player in this field. With the C2M Chair, the exploited platforms focus on exposure to electromagnetic waves. The skills in evidence in these activities bring the chair a considerable level of international recognition.

Handling these platforms at such frequencies requires a level of know-how that is recognized by our academic and industrial partners.

7.2.5 Synthetic self-assessment

Strengths One of the team's main strengths is its multidisciplinary expertise and complementary activities, which enable researchers to contribute to systems or sub-systems, rather than just components or functions.

Weaknesses Increased difficulties in attracting Télécom Paris graduate students into PhD studies in the microwave and millimeter waves field due to their preference for data-related topics (Big data, artificial intelligence, etc.). Collaborations with industrial partners have been attempted but not yet formalized. The team is pursuing its efforts in this direction.

Opportunities The team's new location on the Palaiseau campus enables it to forge closer links with renowned teams such as III-V Lab and Thales and the team is working towards defining suitable research environments. Contacts have been established with Thales, while GaN component characterizations in the millimeter frequency band are ongoing in collaboration with III/V Lab.

Threats The complexity of access to the Palaiseau site (transport, accommodation), the absence of partnerships with national research organizations, and the constant changes in the supervisory structure impact the team's attractiveness.

7.3 Scientific Production

7.3.1 Qualitative analysis

Our research can be divided into two research areas: (i) Antenna and circuit design, co-design, and integration up to millimeter waves and (ii) Stochastic behavioral models for antennas and propagation for '5G and beyond' systems, localization, and human/waves interactions. During the period 2018-2023, the RFM² team has produced 58 journal papers, 62 articles in proceedings, 1 patent, 9 keynote and other invited talks, 5 book chapters, 1 habilitation thesis, and 13 completed PhD defenses. As our research depends heavily on laboratory work and hardware measurements, the scientific production of the team has been affected both by the pandemic restrictions and the move to new premises. However, the team managed to keep the number of journal publications at a similar level during the period 2018-2023, although the number of conference publications and completed PhD theses has dropped.

Topic - Antenna and circuit design, co-design and integration up to millimeter waves

Contributors: Xavier Begaud, Eric Bergeault, Jean-Christophe Cousin, Antoine Khy, Anne Claire Lepage, Reda Mohellebi, Kyriaki Niotaki, Alain Sibille

The team has continued its research on antennas [633, 623] and absorbers [642] design and characterization. As part of the SAFASNAV program (ASTRID Maturation), the team has designed metamaterial (MM) absorbers with composite materials and inks and has also developed new concepts of MM absorbers. This has led to a patent [646] and several publications [611, 644]. The experience acquired with MM absorbers is beneficial for the new research topic of the team into energy harvesting and wireless power transfer. Regarding antenna design, a key contribution in this area is reference [626] that presents the design and the validation of a multi-layer antenna composed of an ultra-wideband radiating element placed between two metasurfaces, one acting as reflector [625, 624] and the other one as superstrate [621, 622]. Such topology allows multiple reflections inside the formed cavity, known as Fabry-Pérot resonances, and takes full advantage of the metasurfaces. The proposed concept is validated with a low-profile directive multiband antenna operating for 5G/4G/Wi-Fi 2.4/5/6E performing beam steering in the 5G without disturbing the radiation patterns of the other bands.

On another subject, reference [614] proposes an advanced linearization scheme to make spatial multiplexing by electronically steerable multiple antennas via a single RF receiver more efficiently usable.

Concerning millimeter-wave antenna design, the results obtained as part of the TWEETHER (H2020) program [641, 636] between 92 and 95 GHz and the ScanVision (FUI) program [612, 613] between 92 and 96 GHz have demonstrated the quality of our measurement equipment.

In references [615, 637, 638, 639, 640], the first design and realization of a multimode TRL calibration kit using CCPW lines on a quartz substrate in the Ground-Signal-Ground-Signal-Ground (GSGS) configuration for on-wafer mixed-mode S-parameter measurements are presented. The good agreement between simulation and measurement results performed on different verification elements demonstrates the validity of two methods up to 40 GHz. As part of a CIFRE agreement with Thales ARV, we are developing an innovative architecture based on a low-loss broadband GaN power-combiner (2-18 GHz) with a 100 W output power level [647].

With the arrival of K. Niotaki in November 2020, complementary expertise in RF and millimeter wave circuits and system design has been added to the RFM² team. Her experience on radiofrequency energy harvesting circuit design [634], along with the existing strengths of the team in antennas and absorbers, has initiated a new research area and has led to two ongoing research PhD topics: millimeter wave energy harvesting technologies and the design of smart metamaterial absorbers with dual functionality, allowing the reduction of electromagnetic pollution on the one hand and the reuse of lost energy on the other.

Topic - Stochastic behavioral models for antennas and propagation for '5G and beyond' systems, localization, and human/waves interactions

Contributors: Jean-Christophe Cousin, Christophe Roblin, Alain Sibille, Joe Wiart

One of the research areas of the team is indoor localization for various applications such as patient monitoring in hospitals and firefighters. Reference [616] focuses on the position estimation of an active tag by a localization base station and provides the measurement results of a proof of concept hardware setup of a 2D impulse response UWB localization system. This work supports the realization of high-resolution localization systems without increasing the frequency bandwidth and is compliant with the power spectral density (PSD) used in UWB.

In the field of radio channel modeling, the team is interested in several different aspects. With the increase in frequency for the 6G standard, joint work is being carried out in collaboration with Orange Labs to characterize the permittivity and conductivity of usual low-loss building materials on the continuous frequency bandwidth of 2-260 GHz [606]. This step is necessary to subsequently establish attenuation models for the 6G standard. Another aspect concerns a novel methodology of statistical modeling of the far field radiated by antennas undergoing random variabilities. It is presented in reference [617]. A robust and efficient adaptive procedure guarantees the accuracy of the surrogate model with a minimized experimental design cost. This methodology is applied

to a 2.4-2.5 GHz band wearable textile patch antenna subjected to five random geometric and material parameters: stretching, bending, torsion and compression (varying substrate thickness). The obtained results can benefit the antenna design and optimization procedures and can be also used for joint antenna channel stochastic analyses. In the context of IoT, new quantitative models of the influence of (i) human morphology, and (ii) the indoor environment on the path loss and delay spread of on-body radio links for Wireless Body Area Network communications have been proposed [649, 650, 651, 652]. The latter was notably based on physics, geometry and stochastic approaches exploiting efficient experimental designs. Reference [620] addresses the distance dependence of reconfigurable intelligent surface (RIS) performance and demonstrates how the physical area, as well as near field vs. far field aspects, are of paramount importance.

Lastly, our team focuses on monitoring the increasing human RF exposure as a result of the deployment of wireless networks, and thus on addressing the continuing perception of risk due to EMF exposure. Today, monitoring EMF exposure, like that carried out by the National Frequency Agency (ANFR), requires numerous measurements. In reference [648], a new approach based on both artificial intelligence (artificial neural networks) mapping exposure with a minimum number of measurements is presented. To that aim, the spatio-temporal exposure induced by an existing 4G cellular network - operating at 2.6 GHz - and located in a district of Paris was measured. Fixed locations were chosen to simulate the measurements of a network of sensors located on lamp posts. Initially, the reconstruction via only the sensor network (and the accessible information) was explored and showed that a fairly large number of fixed sensors was necessary for the reconstruction of the exposure map. A reconstruction method combining cellular network information, artificial intelligence, simulations representing sensor measurements, and street measurements (drive test) was then evaluated. The study shows that this hybrid approach enabled accurate prediction. Following these simulations, a study is underway using real data. Furthermore, in reference [627], the use of stochastic geometry for exposure assessment applicable to any 5G-like frequencies has been introduced. The proposed framework has been applied to measurements carried out in Brussels, Belgium, showing that the model faithfully reproduces real-world values. Reference [632] focuses on the assessment of the contribution of distributed antenna systems on global human exposure, while in reference [629] a novel technique for non-invasive absorbed power density by considering antenna-human body coupling has been introduced.

7.3.2 Potential and dissemination strategy

The team's scientific production is multidisciplinary and proportional to the research potential of the unit. The valorization of research and the publications targeted depend on the topic addressed. While some concepts appear at conferences, the design and proof of concept evaluation of antennas and circuits, along with the modelization validated with measurements are tailored for journal publications. The possibility of filing a patent is always considered before any publication. Young researchers are involved at all stages of research to enable them to contribute to the team's scientific production and also to prepare for the Habilitation degree.

7.3.3 Scientific integrity, ethics and open science

Our publications are accessible on the HAL open science website. Furthermore, the team prefers to publish in open-access journals whenever possible.

7.3.4 Synthetic self-assessment

Strengths A great part of the research addresses long-term and highly topical needs such as national security, public health, wireless communications, and metrology. These requirements are independent of short-term demands and uncertain hype while responding to industrial needs and sovereignty. This ensures stable and long-lasting scientific production.

Weaknesses Attracting outstanding PhD candidates has become challenging in Europe particularly in France, as there is a reduced level of interest among students concerning hardware-related research areas.

Opportunities The team is currently working on new topics such as energy harvesting, 6G, and scientific-based exposure and risk assessment of radiofrequency systems up to millimeter wave frequencies.

Threats The cost of publishing in open-access journals has risen considerably. If the budget dedicated to the valorization of research works remains at the current level, the number of publications will decrease.

7.4 Contribution of Research Activities to Society

7.4.1 Socioeconomic partnerships and interactions

We contribute to standards committees: At the European level, Joe Wiart is chairman of CENELEC TC106x, which is responsible for standards applicable to mobile and base station emissions. In France, Joe Wiart is Chairman of UF 106 of ANFNOR. Eric Bergeault is a member of the scientific committee of the Laboratoire National d'Essais (LNE).

7.4.2 Research valorization and transfer

Research into new electromagnetic absorbers using metamaterials has led to the registration of a patent [646] with the Safasnav project partners (Naval Group, ONERA, SART). Théo Spillebout's current CIFRE PhD with Thales has led to the submission of a patent application.

7.4.3 Science popularization

Anne Claire Lepage taught an introductory course on Space Telecommunications at the Space-school summer school organized by Université Paris Saclay in 2018 and 2019 for 2nd-year bachelor's students. She gives seminars on space telecommunications at a primary school. Every year she takes part in events for high school girls organized at Télécom Paris to promote research and engineering careers for women by describing her research topics and sharing her experience.

Alain Sibille has taken part in several broadcasts and other debates, as well as in 5G training courses for companies and local authorities (run by Netexplo).

Joe Wiart contributes to the dialogue on exposure at different levels: participation in the ANFR dialogue committee, participation in the mobile telephony observatory of the city of Paris, and organization of open seminars. He has also taken part in 5G training courses (run by Netexplo).

Xavier Begaud contributed (as advisor and author [607]) to Techniques de l'Ingénieur on antenna-related topics.

7.4.4 Synthetic self-assessment

Strengths The C2M Chair contributes to the study of risk perception linked to exposure to electromagnetic waves. The team's work on antennas and channels for body-centric networks and patient monitoring are two further contributions to societal needs. We also work with the primary metrology laboratory in France (LNE) to meet the calibration needs of network analyzer users.

Weaknesses The instrumentation for MMIC characterization, metrology, and all millimeter-wave measurement systems are very fragile and it is difficult to present them to the general public.

Opportunities The creation of a new research activity linked to energy harvesting and wireless energy transfer will contribute to a better use of energy resources.

Threats Exposure measurements, metrology, and work on energy harvesting are areas where instrumentation is very costly, particularly in terms of maintenance. A reduction in maintenance budgets would have a direct impact on the amount of work carried out in these areas.

Chapter 8

Self-assessment of SSH team

8.1 Profile, Resources and Organization

8.1.1 Scientific objectives

The scientific objectives of the **SSH team** encompass the development of digital architectures and methodologies tailored toward the creation of efficient, secure, and reliable embedded systems. These systems rely on specialized hardware and low-level software implementations. The motivation behind this pursuit stems from the increasing demands of emerging applications, which impose stringent requirements across various domains such as security, performance, energy efficiency, and cost-effectiveness. This is particularly evident in applications related to 5G/6G telecommunication systems, autonomous vehicles, smart cities, and edge computing for embedded artificial intelligence, all of which operate under challenging conditions.

In alignment with these objectives, the SSH team places significant emphasis on addressing security and safety concerns to ensure the trustworthiness of the proposed architectures. Given the proliferation of threats that compromise privacy, cybersecurity, and system reliability, it is imperative to address vulnerabilities at both the software and hardware levels. This entails safeguarding against failures arising from hostile environments or malicious attacks exploiting physical proximity. The overarching research goal of the SSH team is to devise robust solutions capable of mitigating these diverse threats. This involves leveraging novel resilience mechanisms, alongside innovative digital architectures and technologies, to not only enhance trust but also to optimize performance and address other emerging application requirements. The research efforts of the team are organized into two primary areas:

- Effective architecture design and validation
- Analysis methods to meet stringent constraints

These areas are interconnected, as the insights gained from analysis inform the development of effective architectures and associated design/validation methodologies. Various forms of analysis are employed, including formal abstract analysis, computer simulation, and real-world circuit analysis utilizing FPGAs or custom ASICs developed using cutting-edge CMOS technologies.

8.1.2 Resources

One particularity of the SSH team is the broad range of competencies among its members, including expertise in algorithms, software implementation, digital architectures, circuit design, and practical laboratory skills to be able to develop a robust analysis of real hardware and software implementations. Hence, the team is composed of people with different profiles with complementary theoretical and practical skills. This activity is made possible thanks to a wide range of public and industrial funding sources. A close link with the industrial world, thanks to the practical nature

of these research topics, has been created, allowing the team to maintain several CIFRE PhDs and collaborative projects.

- *Human resources*

Team leader: Jean-Luc Danger (Full Professor) April 2023, Lirida Naviner (Full Professor) since April 2023.

Faculty: Sumanta Chaudhury (Associate Professor), Jean-Luc Danger (Full Professor), Guillaume Duc (Associate Professor), Tarik Graba (Associate Professor), Ulrich Kühne (Associate Professor), Yves Mathieu (Full Professor), Maria Mushtaq (Associate Professor, since September 2021), Lirida Naviner (Full Professor), Alexis Polti (Associate Professor 2020), Laurent Sauvage (Associate Professor), Minhao Yang (Associate Professor since October 2023).

Research Engineers: Abdelmalek Si-Merabet (Research Engineer).

Associate Professors: Hervé Chabanne (IDEMIA), Sylvain Guilley (Secure-IC).

Invited Researcher: Wei Cheng (since July 2022).

PhD Students: Benjamin Coeffic (May 2013-April 2018), Damien Marion (February 2015-December 2018), Eloi De Cherisey (October 2015-December 2018), Khaled Karray (October 2015-April 2019), Fábio Batagin Armelin (January 2016-August 2019), Elaine Crespo Marques (December 2016-December 2019), Michaël Timbert (October 2016-September 2020), Nilson Maciel De Paiva Junior (April 2017-December 2020), Sébastien Carre (September 2017-December 2020), Xuecan Yang (October 2017-March 2021), Sofiane Takarabt (December 2017-July 2021), Oualid Trabelsi (April 2018-July 2021), Linda Guiga (October 2019-June 2022), Etienne Tehrani (September 2018-July 2022), Maxime Ayrault (November 2018-October 2022), Ritu Ranjan Shrivastwa (May 2019-December 2023), Guillaume Soudais (February 2020-), Quentin Forcioli (October 2020-), Felipe Lisboa Malaquias (November 2020-), Arnaud Varillon (October 2021-), Esther Goudet (November 2021-), Maryam Idrees Mughal (September 2022-), Pierre-Augustin Berthet (October 2022-), Maxime Spyropoulos (October 2022-), Neelam Nasir (March 2023-), Luis Humberto Peña Treviño (October 2023-), Matheus Minelli De Carvalho (December 2023-).

- *Laboratory*

The team has an electronics laboratory shared with the C2S team. This laboratory hosts the "Trust Analysis Platform (TAP)" research platform, which is an important tool for practical analysis of the robustness of digital circuits, either by probing physical phenomena or injecting disturbances to create faults.

- *Financial resources*

A continuous effort to obtain research funding is carried out by the team members. This is necessary to procure state-of-the-art laboratory equipment and hire talented students, researchers, and engineers. The team benefits from many types of research funding derived from both national and international sources.

8.1.3 Human resources management, safety, environment, ethical protocols, data and scientific heritage protection

Team meetings are held every month. Some additional meetings take place for specific events, such as the recruitment of new faculty members or for brainstorming purposes concerning educational programs. The team recognizes the importance of diversity and inclusion. We are mindful of the need for equal opportunities and fair representation. We continue to strive towards fostering an environment where all members, regardless of gender or background, can thrive and contribute meaningfully. In line with the laboratory policy, the team is sensitive to sustainable development. It notably limits travel when a virtual meeting is possible. The same applies to conferences where local and virtual conferences are preferred, or the number of physical attendees is limited to one researcher.

Type	Number
ANR (excepting IDEX)	6
Bilateral	5
Carnot	4
Chair & Commun Lab	1
Cluster Saclay	3
CIFRE	7
European	1
IPP	2
SATT	1
Public (excepting ANR)	3

TABLE 8.1: Funding sources.

2018-2023 (K€)							
	2018	2019	2020	2021	2022	2023	Total
Public National	67	58	105	73	96	360	759
International		43	47	47	4	146	287
Partnership & Transfer	371	323	471	185	165	279	1,794
Total	438	424	623	306	265	785	2,840

TABLE 8.2: Funding amounts.

8.1.4 Synthetic self-assessment

Strengths: The team benefits from a diverse array of human resources, boasting individuals with complementary theoretical and practical skills, thereby enhancing the team’s overall capabilities and effectiveness.

Weaknesses: Challenges in recruiting and retaining human resources, including post-docs and engineers, may hinder the team’s ability to fully execute its research agenda.

Opportunities: The increasing demand for expertise in security and reliability for embedded systems presents promising avenues for additional research funding and collaboration.

Threats: Intense competition for talented researchers in the field of embedded systems may pose challenges to recruitment efforts.

8.2 Attractiveness

The team maintains strong relationships with the industrial sector as well as other national and international laboratories. This diversity of collaborations allows for the proposal of various types of PhD topics, ranging from those closer to industry with significant design work to those closer to academia with a more theoretical approach.

8.2.1 Scientific reputation and contributions

Members of the SSH team hold positions on the executive board of the doctoral school, ensuring effective governance and strategic direction for graduate education. They also play integral roles in selecting doctoral candidates for thesis funding competitions and participate in various doctoral contests, such as Best Thesis and Best Scientific Production. Furthermore, SSH faculty members contribute to the academic community by serving on professor selection committees for universities and participating in thesis committees both nationally and internationally. They are actively involved in the technical committees of numerous conferences, shaping the discourse and direction

of research in their respective fields. Moreover, SSH faculty members serve as reviewers for several scientific conferences and journals, upholding the standards of quality and rigor in academic publishing. Their expertise is recognized internationally, as evidenced by invitations from foreign universities to present lectures and collaborate on research projects.

8.2.2 Staff hosting policy

During the concerned period, the team recruited three new associate professors. Despite some conjectural difficulties in recruiting talented researchers in the last few years, the team was able to attract both young and established researchers nationally and internationally.

- Maria Mushtaq, PhD in 2019 from the University of South Brittany. Recruited in 2021 with expertise in microarchitectural vulnerability assessment and mitigations.
- Minhao YANG, PhD in 2015 from ETH Zürich. Recruited in 2023 with expertise in mixed-signal design for energy-efficient intelligent systems.
- Jianyi Yang, PhD in 2023 from the University of California, Riverside. Expected to join the team in 2024, with expertise in machine learning for embedded systems.

In addition, the team has a history of inviting sabbatical professors from international institutions such as Tohoku University, Kobe University, and the Chinese Academy of Science. During the evaluation period, this hosting activity almost came to a halt, mainly as a result of the restrictions during the Covid-19 pandemic. One researcher from Le Quy Don Technical University spent one year in association with the team during the pandemic period, with limited physical meetings. Furthermore, the team has established robust collaborations with industrial partners, exemplified by the welcoming of invited professors from key players such as Idemia, as part of a joint research laboratory, and Secure-IC.

8.2.3 Success in competitive calls for projects

- Funding \geq 100,000 euros
 - ANR: SECODE, 2016-2019
 - ANR: ARCHI-SEC, 2019-2024
 - ANR: APRIORI, 2021-2024
 - ANR: ARSENE, PEPR Cyber, 2022-2025
 - ANR: TCE (Train Cyber Expert), 2023-2027
 - ANR: SODA (SoC Design Levering AI), 2023-2026
 - Bilateral PSA: PCA Cyber-Sécurité des véhicules connectés, 2015-2018
 - Bilateral THALES: PISTIS (Progression des Techniques de Fiabilité Prévisionnelle), 2015-2020
 - Carnot: PhD thesis YANG Xuecan, 2017-2020
 - Carnot: PhD thesis CHENG Wei, 2018-2021
 - Carnot: PhD thesis IDREES Mariam, 2021-2024
 - Carnot: PhD thesis BOURGEOISAT Doran, 2022-2025
 - Fondation Mines Télécom: Chaire C3S (Connected Cars & Cybersecurity), 2017-2023
 - European Comission H2020: SPARTA, 2019-2022
 - CR IdF: CSAFE, FUI Regions, 2017-2021
 - Paris Region IdF: DIM-RFSI Deep Learning, 2021-2027
 - BPI France: X7PQC (France 2030), 2022-2026
- Funding $<$ 100,000 euros

- Bilateral CBE: Expertise Codes Source VHDL, 2020
- DGA AID: 1/2 PhD thesis Arnaud VARILLON (co-funding ANR IA), 2021-2024
- DGA AID: 1/2 PhD thesis Maxime SPYROPOULOS (co-funding THALES), 2022-2025
- FCS UPSAY: Spin TCAM, 2017-2019
- DigiCosme - Post-doc GT SASEFOR, 2017-2018
- DigiCosme - Initiative Transverse NewEmma Alaa MAZOUZ, 2022-2023
- CIFRE Secure-IC: MARION Damien, 2015-2018
- CIFRE Secure-IC: TIMBERT, 2016-2019
- CIFRE Secure-IC: CARRE Sébastien, 2017-2020
- CIFRE Secure-IC: TAKARABT Sofiane, 2017-2021
- CIFRE Idemia: GUIGA Linda, 2019-2022
- CIFRE NOKIA: SOUDAIS Guillaume, 2020-2023
- CIFRE ST Microelectronics: GOUDET Esther, 2021-2024
- IP Paris (ANR IA): 1/2 PhD thesis Arnaud VARILLON (co-funding AID-DGA)
- IP Paris: Prématuration Approxinet, 2021-2023
- DigiCosme - Post-doc (project PROCRASST)
- APPROXINET SATT PARIS SACLAY PoCUP

8.2.4 Equipment quality and technological skills

One source of added value provided by SSH is notably its technical competencies in the design of VLSI circuits, in addition to the validation and analysis of real circuits in its laboratory. The know-how to design circuits as application-specific integrated circuits (ASIC) is a competence requiring exceptional expertise and is not especially common among academics. It enables the team to use recent CMOS technologies in addition to programmable circuits (FPGA) which are more frequently used.

8.2.5 Synthetic self-assessment

Strengths: The SSH team is renowned for its close industry and academic collaborations, recognized research reputation, and successful recruitment of top talent.

Weaknesses: Maintaining attractiveness to retain top talent and secure ongoing funding amidst increasing competition in the field may pose challenges for the team.

Opportunities: Recent recruitments and technical expertise enhance mentoring and collaboration capacities while positioning the team for funding in emerging technology fields.

Threats: Increased competition for funding and talent, alongside economic uncertainties, may affect the team's sustainability.

8.3 Scientific Production

8.3.1 Qualitative analysis

Publications 2018-2023 (source HAL)					
Year	Journals	Conference	PhD	Others	Total
2018	11	23	0	4	38
2019	11	23	1	8	43
2020	11	22	1	0	36
2021	14	25	4	8	52
2022	14	23	3	0	42
2023	7	20	2	1	32

Topic - Effective Design to Meet Stringent Constraints

Contributors: Sumanta Chaudhuri, Jean-Luc Danger, Yves Mathieu, Lirida Naviner, Tarik Graba

Effective architectures for communications In [925] we addressed the challenge of sparse channel estimation within Software-Defined Radio (SDR) systems, driven by the imperative of enhancing communication reliability in dynamic environments. Investigating sparse recovery algorithms, compressive sensing (CS) techniques, and neural network-driven methodologies, we aimed to unlock new capabilities in accurately estimating channel state information (CSI) while mitigating computational complexity [927]. Our contributions ranged from novel algorithmic developments like Matching Pursuit based on Least Squares (MPLS) for efficient channel sparsity exploitation to wideband HF channel estimation, extending the applicability of sparse estimation techniques [926, 964]. Furthermore, we explored neural network architectures, proposing enhancements to algorithms such as LISTA and introducing tailored models for sparse signal estimation tasks [971, 970]. In [969], we focused on hardware-centric solutions for spectrum sensing in Cognitive Radio (CR) networks, aiming to address the challenges posed by finite radio spectrum resources. We have investigated single-event transient (SET) effects on dynamic comparators within 28nm FDSOI CMOS technology [965]. Continuing our investigation, we conducted a reliability analysis of NAND-like spintronic memories [963]. Additionally, we explored the effects of event transients on voltage-controlled magnetic anisotropy MeRAM bit-cells, as discussed in [966]. Furthermore, we proposed a Magnetic Tunnel Junction-based Analog-to-Digital Converter utilizing the Spin-Orbit Torque Mechanism [968, 967]. Regarding digital infrastructures, we explored the integration of latency, reliability, and jitter-constrained applications over standard information technology networks [983, 984], leading to the creation of an operational hardware demonstrator [907].

MTJ based circuits In our exploration of MRAM technology integration, diverse research has been conducted, emphasizing critical aspects. Studies on low power consumption include investigations into ultra-low-power access strategies [1000], stability-focused STT-MRAM sensing circuits [950], and writing-only in-MRAM computing paradigms [961]. Efforts to enhance reliability include research on reliability-emphasized MTJ/CMOS hybrid circuit [911], failure and aging degradation mitigation in MRAM/MeRAM-on-FDSOI integration [914], and dependable STT-MRAM with emerging approximation and speculation paradigms [912]. Exploration of CMOS-MTJ hybrid circuits encompasses studies on hybrid MTJ-CMOS integration for sigma-delta ADC [996], resilient voltage-controlled MeRAM using write assist techniques [915], and voltage-controlled magnetic anisotropy MeRAM bit-cell over event transient effects [966]. Computing in memory paradigms include sparse realization in unreliable spin-transfer-torque RAM for convolutional neural networks [910], cryogenic in-MRAM computing [891], and pulse shape induced failure analysis in voltage-controlled MRAM [962]. Investigations into MRAM architectures involve exploring MRAM-on-FDSOI integration [913] and MTJ-based stochastic computing in deep learning [994].

Radiation-induced faults in memories The escalating vulnerability of memory devices to radiation-induced faults necessitates robust error correction techniques, particularly in critical applications where system failures pose significant risks. We proposed innovative approaches to enhance ECC efficacy, such as the integration of Line Product Code (LPC) with specialized decoding algorithms. In particular, employing a combination of single and double error correction algorithms tailored to exploit LPC characteristics, the proposed algorithms demonstrate efficiency in decoding LPC codewords, improving error correction potential while optimizing implementation costs [945, 947]. In addition, this study introduced a refined ECC variant derived from PCoSA (Product Code for Space Applications). Through testing and comparative analysis, the proposed solution exhibits superior error correction capabilities, effectively addressing specific error patterns and burst errors while maintaining high reliability and hardware efficiency [946].

Embedded AI In [997] we focused on making Convolutional Neural Networks (CNNs) more suitable for deployment in embedded systems with limited computing resources and memory, and

proposed three methods for accelerating neural networks. The *Selective Binarization* method combines layers with different precisions in CNNs to achieve acceptable speed and accuracy. An FPGA-based hardware accelerator is also proposed for these optimized structures. The *Quad-Approx Network* method involves quantizing CNNs into 3 bits using a proposed activation function called signed PACT, followed by establishing a loss-less network using an approximate multiplier. An FPGA implementation of an approximate multiplier for 3-bit multiplication is also proposed, resulting in significant speedup and compression when applied to a Quad-Approx Network. The *MinConvNets* method involves creating multiplication-less CNNs where multiplications are replaced by approximate operations. MinConvNets achieve a negligible loss of prediction compared to exact image classification networks through transfer learning [999, 998].

Digital sensors for online security and reliability The sensors are generally built with analog components. In order to use them in a portable way in all digital technologies, we studied a fully digital sensor relying on a Time to Digital Converter (TDC) which is composed of a delay chain and registers. The objective is to measure the propagation time along the delay chain to detect any variation caused by an external disturbance. We studied it specifically to be able to detect any abnormal behavior caused by failures or attacks [897, 939] or indicate the temperature and voltage in digital circuits [951] by using pairs of TDCs. The impact of aging [953] and the ways to reduce it [898] were covered. The TDC was tweaked to be able to take into account the specificity of faults injected by laser where the Power Distributed Network (PDN) is impacted by the induced current [940, 941]. It has been shown in [981, 982] that the detection efficiency can be improved by using a set of digital sensors and machine-learning algorithms.

Security primitives exploiting randomness Randomness in digital circuits is either dynamic if it comes from noise, or static when the noise comes from the fabrication process and is fixed in the circuit. The first type of randomness is to generate True Random Number Generators (TRNG) and the second is to develop the circuit's fingerprint or Physically Unclonable Function (PUF). The SSH team carried out designs and analysis of new TRNG and PUF primitives. A comprehensive overview of the testing of these primitives has been provided in [896]. One of the new proposed architectures which can take the form of both TRNG and PUF relies on the use of Set-Reset latches near metastable state [936]. Delay-PUF is one class of PUF structures that has been extensively studied. Its reliability is the main problem and has been formally expressed in [979, 978, 980]. The impact of aging has been analyzed in [952]. Loop-PUF is one kind of delay PUF proposed by SSH in 2013 that has been efficiently protected against side-channel analysis (SCA) [985]. The Loop-PUF structure has been enhanced in terms of reliability and entropy in [932]. A reduction of its complexity by keeping good reliability properties has been analyzed in [906]. Its security analysis against SCA has been carried out and improved in [986, 987]. The Arbiter-PUF is another popular delay PUF which has been rigorously analyzed against SCA [958, 929, 957] and protections have been proposed in [934, 959, 935].

Secured processors The team worked on novel processor architectures to make them more secure or faster to execute cryptographic functions. The first research topic was to propose an efficient Control Flow Integrity (CFI) mechanism to check that the code is not jeopardized at run-time. The proposed CFI is built natively into the hardware architecture of the processor and it allows not only the integrity of the flow to be checked but also the integrity of basic blocks in the case of fault injection. It relies on a specific caching methodology and the use of metadata to compare the integrity of the execution flow [931, 930]. A demonstrator platform using a RISC-V processor has been built to validate the concept. The objective of a second research topic was to accelerate the code execution of lightweight symmetric cryptographic blocks. The new architecture is generic and can execute most of lightweight cryptographic functions with a speed-up factor which can be 100 [988, 991, 989]. Moreover, the architecture has been enhanced to be robust against first-order side-channel analysis [990].

Topic - Analysis Methods and Tools

Contributors: Jean-Luc Danger, Guillaume Duc, Ulrich Kühne, Maria Mushtaq, Lirida Naviner,

Laurent Sauvage

Radiation-induced faults in Digital Circuits Soft Error Vulnerability (SEV), a crucial parameter in predicting Soft-Error Rate (SER) in digital electronic systems exposed to particle radiation, remains a challenge to estimate accurately. While radiation testing provides precise SER estimation, it is costly and requires the circuit, which is typically available only late in the development cycle. We proposed an approach for SER estimation using electrical pulses that allows for Single Event Transient (SET) emulation in sequential circuits, thus offering advantages in terms of estimation speed [900]. We introduced a method for probability-aware fault injection that improves upon traditional approaches by introducing a weighted fault distribution that accounts for the relative fault probability of each functional element, and substantially decreases the need for logic blocks [899]. We proposed a strategy for estimating SEV, which considers SET susceptibilities, offering simplified and comprehensive versions to capture topological effects or incorporate circuit operation, respectively. Evaluation on several reference circuits demonstrated improved accuracy with both versions and the feasibility of adopting the proposed strategy is validated through emulation-based approaches, highlighting its practical applicability [905, 904]. In [948] we concentrate on scenarios where a soft error occurs in a combinatorial circuit while assuming ineffective electrical and timing masking effects. Our objective is to compute the error rate (or the correctness rate) of combinatorial circuits considering only the logical masking effect. We propose a novel probabilistic and partitioning approach called the Clusterized Probability Reliability Model (CPBR) that reduces the complexity of processing significant circuits while maintaining high accuracy in error rate calculations [949].

Faults injected in digital circuits This research aims to study the fault model in laser fault injection (LFI) to extract secrets into a System on Chip with a microcontroller. It has been shown in [924, 974] that the flash memory interface is particularly sensitive to LFI and generates instruction skips. By refining the setup and the location of the laser shots, the fault model can be extended to replay instruction [955] and can even target the microcontroller pipeline at specific locations [954]. Another example of research focuses on analyzing the fault injected by electromagnetic (EM) probes. The probes have been first characterized [993] before using them on pure combinatorial logic [992] and real microcontrollers [972] causing faults at the flash interface which give rise to instruction skips and instruction replays at software level [973, 938, 956]. When the target is an FPGA, the EM injection creates faults induced by timing modification as in the case of microcontrollers but also targets the clock network [975] which shows the limits of certain sensors to detect faults [976].

Security analysis of connected cars As part of the research chair C3S (*Connected Cars and Cybersecurity*), we have notably contributed to the topics: *Risk analysis and safety*, *Resilience by design* and *Intrusion detection systems*. In the research area *Risk analysis and safety*, in collaboration with the LabSoC team, we have studied the interactions between the design of a system, the attack trees, and the countermeasures: when a countermeasure is added to a system to prevent an attack, new attack scenarios can be added to the system, as the countermeasure is composed of hardware or software components that can themselves be attacked. In [908], we have presented a method to find the optimal selection of security countermeasures to be added to a system with a constraint on the total cost of the system. In the research area *Resilience by design*, we have looked into proactive defense techniques against cyber attacks on connected vehicles. In [901], we have analyzed the effectiveness of different moving target defenses (MTDs) in the context of connected vehicles. In the subsequent research, these and other defenses have been integrated in a game-theoretic framework, to find an optimal defense strategy for an entire vehicle, and take into account different types of adversaries in a probabilistic manner. The resulting model uses mixed integer linear programming (MILP) to compute the best system configuration [903, 902]. Concerning the topic *Intrusion detection systems* (IDS), a first study relying on supervised learning and outlier detection on CAN bus attacks has been carried out [942]. The ethernet-based network has then been considered for IDS, first using supervised learning on the SOME/IP

protocol [892] and then by using unsupervised learning on the AVTP protocol [894]. The SOME/IP IDS has been significantly increased by taking advantage of transformers that handle ordered sequences of data [895]. Transformers, more specifically bidirectional encoder representations from transformers (BERT) have been efficiently tested on CAN-bus IDS [893] proving the validity of the approach.

Side-channel analysis on mask-based protections An important study was to evaluate the efficiency of the masking schemes as protection against SCA. A comprehensive overview is given in [933]. Masks derived from error-correcting codes were considered to better formalize and optimize their efficiency. It was demonstrated that masks such as Inner Product Masks (IPM) can not only protect against SCA but can also detect injected faults [919, 920]. The optimal IPM codes have been formally found in [922] before considering all types of code-based masks [921]. Leakage has been assessed theoretically [923], and pragmatically [995], allowing the comparison of codes for different orders of attacks.

Penetration testing for Micro-Architectural Security with gem5 In [944] we present an overall description of a pen-test platform called Archi-Sec, capable of emulating most of the known micro-architectural attacks including Spectre/Meltdown, Cache Timing Attacks, Rowhammer, and attacks from 3rd party Accelerators such as GPU/FPGA. In [943] we present a gem5 based platform capable of booting the open-source *Trusted Execution Environment* OPTEE, in addition to demonstrating several different types of attacks on it, namely in-vitro attacks on EmbedTLS library, and in-vivo attacks on the OPTEE OpenSSL. In [943] we present a dynamic cache-timing analysis tool based on our platform Archi-Sec, which can identify information leaks in executable code in real settings, i.e. taking into account cache policies, prefetch policies, cache parameters, etc. and we outline a practical example using OPTEE. The work of Archi-Sec is later extended by means of three ANR projects; PEPR- ARSENE, BPI-X7PQC and SCAMA. The focus of these projects remains on automated vulnerability assessment of timing-based cache side-channel attacks and providing Operating System (OS) based mitigation solutions for these side-channel attacks. X7PQC argues in favor of detecting side-channel attacks on post-quantum crypto applications on FPGA and hardware-assisted platforms. Moreover, with the ANR-PEPR-5G project, we remain focused on the modeling and verification of new AI-based techniques for side-channel attack anomaly detection and prevention. With this project, we aim to design a new system and verification approach that can handle systems with secure detection modules and with network features such as 5G.

Security of artificial neural networks While artificial intelligence - in particular artificial neural networks - can be used for security, we also need to take care of the security *of* these networks. Indeed, due to the high level of development effort and computational costs, the established models are considered valuable intellectual property (IP). In [916], we provide an overview of existing attacks on neural networks. Such attacks rely on side-channel information collected during the inference to extract the exact structure and parameters (weights) of the network. In [917], a protection mechanism is presented, based on randomizing the calculations during inference. The approach has also led to a patent [928]. Further protection techniques are presented in [918] and [909].

8.3.2 Potential and dissemination strategy

The dissemination strategy of the SSH team aims to ensure the broadest possible impact of our findings within both academic and non-academic communities. Faculty and doctoral students are encouraged to disseminate their research findings through presentations at national and international conferences. Additionally, they are expected to publish their work in peer-reviewed journals, with an emphasis on high-impact publications. The SSH team actively participates in organizing workshops, symposiums, and seminars, both within academia and in collaboration with external stakeholders. Participation in national events allows for recognition, anchoring, and reinforcement within the French community, while participation in international events fosters greater visibility and dissemination on a global scale.

8.3.3 Scientific integrity, ethics and open science

The SSH team upholds rigorous ethical standards in all research activities. Our publications prioritize open-access dissemination through platforms like HAL, ensuring broad accessibility. Embracing open science, we promote data sharing, reproducibility, and collaboration, advocating for equitable access to scholarly resources.

8.3.4 Synthetic self-assessment

Strengths: High volume of publications, demonstrating sustained research activity.

Weaknesses: Fluctuations in publication output.

Opportunities: Opportunities to explore emerging research areas and strengthen interdisciplinary collaborations.

Threats: Risks associated with increased competition for funding and talent, as well as rapid technological advancements and evolving regulatory frameworks.

8.4 Contribution of Research Activities to Society

8.4.1 Socioeconomic partnerships and interactions

SSH maintains extensive collaborations with industrial partners, fostering meaningful interactions between academia and the socioeconomic sphere. These partnerships are integral to addressing real-world challenges and ensuring the applicability of our research. A notable aspect of SSH's engagement with the socioeconomic world is the numerous collaborative doctoral projects undertaken with industrial partners. These projects not only provide financial support for Ph.D. candidates but also facilitate the transfer of knowledge and expertise between academia and industry.

8.4.2 Research valorization and transfer

Throughout their doctoral journey, students are supported in identifying potential patents or intellectual property arising from their research. Faculty collaboration with industry partners is encouraged to facilitate technology transfer and real-world application of research outcomes. The PhD thesis "Approximate Computing Techniques for Embedded Machine Learning" by Xuecan Yang led to the technology transfer project Approxinet which was later selected by the IP Paris *Prématuration* (2022) and SATT Paris-Saclay PoCUP (2023) (see 2.1.6).

8.4.3 Science popularization

As part of the C3S research chair, several articles and interviews have been published in mainstream media to raise awareness and answer questions from the general public on the subject of cybersecurity in connected and autonomous vehicles. These included an interview on the Parigo program (France 3 Île-de-France) and another one on France Culture.

8.4.4 Synthetic self-assessment

Strengths: Extensive collaborations with industrial partners, engagement in science popularization, and active participation in technology transfer initiatives.

Weaknesses: Limited exploration of dissemination channels for research outcomes.

Opportunities: Potential to broaden science popularization efforts across diverse channels, enhancing engagement with various audiences and increasing societal impact.

Threats: Changing communication trends necessitates ongoing adaptability and innovation in dissemination approaches.

Chapter 9

Self-assessment of ACES team

9.1 Profile, Resources and Organization

9.1.1 Scientific objectives

The Autonomous Critical Embedded Systems (ACES) team operates at the forefront of computer science with a clear focus on addressing contemporary challenges through research in the following areas: cybersecurity, safe and secure distributed systems, software engineering, embedded real-time systems, and autonomous and energy-aware systems. The team's scientific objectives are as follows:

Cybersecurity: To enhance digital security, the team aims to define robust protocols for secure object management, develop adversarial methods to challenge intrusion detection systems, and devise optimal defense strategies for critical systems using game theory.

Safe and Secure Distributed Computing: The objective is to establish reliable data access and consensus protocols that optimize energy consumption, throughput, and latency while ensuring robustness against Byzantine attacks and improving data protection techniques.

Software Engineering: The team seeks to advance both empirical and model-based approaches in software engineering. Objectives include managing the world's largest archive of software source code for security and developing methods for early detection and correction of design errors in software development.

Embedded Real-Time Systems: The aim is to improve the reliability and performance of mixed-criticality systems and predictable computing within real-time embedded systems, focusing on scheduling, timing analysis, and optimization under resource constraints.

Autonomous and Energy-Aware Systems: The objective is to develop systems that are self-adaptive, environmentally friendly, and energy-efficient, with projects like SmartGarden exemplifying the application of these principles for societal benefit.

Each of these objectives is pursued through a combination of theoretical and applied research, collaboration with external partners, and active dissemination of results through top-tier publications and contributions to open-source projects. Integrity, ethics and a commitment to open science underpin the team's activities. Through a focus on these diverse yet interconnected domains, the team pushes the boundaries of scientific and technological knowledge and addresses urgent practical challenges related to security, efficiency, and sustainability in computing.

9.1.2 Resources

Human resources

Team leader: Laurent Pautet (Full Professor) until September 2022, Ada Diaconescu (Associate Professor) from September 2022 to November 2023, Samuel Tardieu (Associate Professor)

since November 2023.

Faculty: Dominique Blouin (Associate Professor), Étienne Borde (Associate Professor, until February 2022), Florian Brandner (Associate Professor), Ada Diaconescu (Associate Professor), Petr Kuznetsov (Full Professor), Jean Leneutre (Associate Professor), Vadim Malvone (Associate Professor, since July 2020), Gérard Memmi (Full Professor), Mounira Msahli (Associate Professor, since July 2020), Élie Najm (Full Professor, until August 2019, then Emeritus until June 2022), Laurent Pautet (Full Professor, 70%), Matthieu Rambaud (Associate Professor, October 2018-November 2022), Thomas Robert (Associate Professor), Samuel Tardieu (Associate Professor, 50%), Sylvie Vignes (Associate Professor, Emeritus until December 2020) Stefano Zacchiroli (Full Professor, since September 2021), Théo Zimmerman (Associate Professor, since December 2022).

Long-term invited professor: Pierre Jouvelot.

PhD students : Maxime Ayrault (November 2018-October 2022), Gabriel Ballot (since October 2022), João Paulo Bezerra de Araújo (since February 2021), Anish Bhobe (since October 2023), Benjamin Binder (October 2019-December 2022), Dorian Bourgeoisat (since October 2022), Maxence Brugeret (since May 2023), Hassan Chaitou (March 2020-September 2023), Florian Champenois (since November 2020), Lijun Chi (since November 2021), Léopold Clément (since November 2023), Luís de Oliveira Soeiro (since October 2022), Louisa Jane di Felice (October 2016-January 2021), Antoine Durand (September 2017-November 2021), Luciano Freitas de Souza (since September 2021), Aloysio Galvalo Lopes (since October 2022), Farouk Hebbache (since November 2019), Étienne Houze (June 2019-June 2022), Katarzyna Kapusta (since December 2018), Dimitrios Kokkonis (since December 2022), Victor Languille (since December 2022), Nan Li (December 2019-March 2023), Felipe Lisboa Malaquias (since October 2021), Julien Malka (since November 2023), Roberto Medina (October 2015-January 2019), Jean Oudot (since October 2017), Franco Petrone Cordeiro (since October 2022), Arles Rodríguez Portela (October 2015-April 2019), Mingming Qiu (February 2019-April 2023), Grégor Quetel (since October 2023), Guillaume Quispe (since December 2022), Solal Rapaport (since October 2023), Samuel Reyd (since October 2023), Thibault Rieutord (September 2015-October 2018), Lilia Rouize (since December 2023), Guy Saadon (May 2016-November 2022), Ibrahim Sadek (March 2015-April 2018), Jacques Samain (February 2016-March 2019), Andrei Tonkikh (since October 2021), Renaud Torfs (since October 2022), Nicolas Van Cauter (since September 2020).

Post-doctoral students: Elena Berardini (September 2021-January 2022), Davide Catta (March 2022-May 2023), Katarzyna Kapusta (2019), Bimal Mandal (November 2021-November 2022), Hana Mkaouar (November 2018-October 2021), Rizwan Parveen (since July 2023), Abdul Wahid (September 2021-September 2022).

Research engineers: Gabriel Ballot (September 2021-October 2022), Ismail Ziad (February 2016-December 2018), Jad Khatib (September 2017-September 2019), Victor Languille (October 2020-December 2021), Ali Mustapha (October 2022-October 2023), Mingming Qiu (November 2018-January 2019), Artur Rataj (September 2018-August 2019), Akshaya Ravi (May 2021-April 2022), Kameswar Vaddina (until December 2018).

Interns: 62 interns.

Financial resources

In addition to the team members' salaries, hosting, and equipment provided by Télécom Paris and the LTCI, team members are proactive in securing additional resources. These resources are utilized to fund doctoral, post-doctoral, and graduate students, as well as equipment and travel budgets.

During the reporting period, the team has collectively secured approximately €500,000 per year through industrial contracts, projects obtained via competitive calls, chairs, and awards. This figure does not include doctoral students' salaries that are funded through scholarships or CIFRE contracts.

9.1.3 Human resources management, safety, environment, ethical protocols, data and scientific heritage protection

In 2019, when Télécom Paris relocated to Palaiseau, the ACES team centralized its offices, enhancing team cohesion with monthly meetings. Despite efforts to promote gender balance in computer science and electrical engineering, from 2018 to 2023, the team saw the addition of two women (one in January 2024) and three men, although efforts are ongoing to create bias-free job descriptions to encourage more diverse applicants.

The ACES team is committed to sustainable development. In line with the LTCI policy, conference travel is limited to one researcher per published paper or proposed workshop. Additionally, one of the team's flagship projects, SmartGarden, is part of the Energy for Climate (E4C) interdisciplinary center. It emphasizes energy and resource savings by utilizing sustainable resources through frugal computing and renewable energy sources.

9.1.4 Synthetic self-assessment

Strengths: The team's size remained stable with strategic new hires, including a distinguished full professor, overcoming retirements and departures.

Weaknesses: There are only three full professors available who can fully supervise PhD students, which may limit the team's capacity for doctoral mentorship.

Opportunities: The potential of having three members complete their HDR next year could expand co-supervision capacities and alleviate current bottlenecks.

Threats: The absence of dedicated research engineers places extra burdens on team members who are required to maintain platforms and software, detracting from their research productivity.

9.2 Attractiveness

9.2.1 Scientific reputation and contributions

The members of the ACES team actively participate in the life of the scientific communities to which they belong. This is reflected in various aspects: participation in organizing or review committees, invitations to deliver keynote speeches or presentations at conferences, involvement in research steering or governance bodies, and editorial responsibilities.

Editorial responsibilities

During the period covered by the evaluation, ACES team members have held significant editorial responsibilities that solidified their reputations in the scientific community. They have served as associate editors for renowned publications or committees, or guest editors for special issues of top journals, such as:

- Member of the IEEE Software editorial board and associate editor for the "open source" theme
- Associate editor: ACM TAAS "Transactions on Autonomous and Adaptive Systems", and IEEE T&S "Technology and Society" Magazine
- Management committee member of the European COST Action Connecting Education and Research Communities for an Innovative Resource Aware Society
- Guest editor: "ACM TAAS Special Issue on 20 Years of Organic Computing, Engineering Continually Adapting Systems", and "AI: Special Issue on Socio-Technical Ecologies: Design for Human-Machine Systems"

Organization of scientific events and research

Team members have served as chairs, co-chairs, and global chairs for tracks and topics at critical conferences, including "Logical Aspects of Multi-Agent Systems & Strategic Reasoning Workshop" (LAMAS&SR 2023), "Sustainable and Scalable Self-Organization Workshop"(SASSO 2023), "Workshop on Strategies, Prediction, Interaction, and Reasoning" (SPIRIT 2023), "European Conference on Multi-Agent Systems" (EUMAS 2023), IEEE "Real-Time and Embedded Technology and Applications Symposium" (RTAS 2022), "International Conference on Real-Time Networks and Systems" (RTNS 2022), IEEE "Conference on Self-Adaptive and Self-Organizing Systems" (SASO 2019), "International Workshop on Self-Improving System Integration" (SISSY 2019-2023), IEEE "International Conference on Autonomic Computing and Self-Organizing Systems" (ACSOS 2019-2023), "Int. European Conference on Parallel and Distributed Computing"(EuroPar 2018), "International Workshop on Worst-Case Execution Time Analysis" (WCET 2018), "Stabilization, Safety and Security of Distributed Systems Symposium" (SSS 2018), and "Software Engineering for Intelligent and Autonomous Systems Seminar" (SEFIAS 2018).

In addition to the events they organize, team members are active as recurring program committee members of several prestigious conferences. Among them, we can name the three top conferences on real-time systems: IEEE "Real-Time and Embedded Technology and Applications Symposium" (RTAS 2019-2023), IEEE "Real-Time Systems Symposium" (RTSS 2021-2023), "Euromicro Conference on Real-Time Systems" (ECRTS 2021-2023), in addition to the "International Conference on Reliable Software Technologies"(AEiC 2018-2023), and many others.

Members of the ACES team have also taken on administrative responsibilities in governing bodies at various levels: member of the National Council for Higher Education and Research (CNESER), board member at the IP Paris, board member at Institut Mines-Télécom, member of the HDR committee at Université Paris-Saclay, member of the academic counsel of Université Paris-Saclay, board member of IRT SystemX, Dean of Faculty at Télécom Paris, deputy director of LTCI, board member of LTCI, board member of Télécom Paris, member of the qualification commission to become Full Professor at Télécom Paris, and head of the Networks and Computer Science department at Télécom Paris.

One member holds the "Trustshare" chair, while another is the scientific head of the "Cyber" chair focused on digital sovereignty and cybersecurity. ACES members also participate in the steering committees of the "Connected Cars and Cybersecurity" (C3S), "Trustshare", "Harvest", "Innovation et Services Numériques" (CSN) and "Valeur Ajoutée Données et Énergie" (Valadeo) chairs, the Seido laboratory with EDF, and of the Energy for Climate (E4C) interdisciplinary center of IP Paris.

Team members are active in several research associations in their domains: IEEE, ACM, CNRS GDR GPL and CNRS GDR SoC2.

Invitations and awards

ACES team members are regularly solicited to share their insights on their respective research areas. For example, they have delivered keynotes at SSS 2019, at the Conference on Principles of Distributed Systems (OPODIS 2021), and at the 2022 CNRS GDR Security plenary meeting. They are also frequently invited to give talks at conferences or workshops such as "Journée Infrastructures pour la Souveraineté Numérique" by Société Informatique de France (SIF), the Paris Systematic workshop on "Sécurité de la Supply Chain logicielle", "SFB MAKI Scientific Workshop on Self-Organizing Systems", "Symposium on Addressing the Role of Digital Technologies in Responding to the Grand Challenges of Environmental Change, Hierarchical Self-Organizing and Self-Adaptive Systems for Understanding & Managing Complexity", GDR GPL 2023, Open Science Days at UGA 2023, the BotSE workshop associated with the "IEEE/ACM International Conference on Software Engineering" (ICSE 2023) conference, or at the "School on Practice and Theory of Distributed Computing" in 2019, 2020, and 2023. They also gave talks at prestigious institutions, such as the CERN, TU Wien, Colorado State University, or KTH Royal Institute of Technology. ACES team members are also frequently invited to participate in scientific panels.

They have also received several awards:

- Best Paper Award: "International Symposium on Distributed Computing" (DISC 2019), "Conference on Real-Time Networks and Systems" (RTNS 2020 and 2022), "Formal methods" (FM 2023)
- Outstanding Paper Award: IEEE "Real-Time Systems Symposium" (RTSS 2018)
- Data and Tool Showcase Award: IEEE ACM "International Conference on Mining Software Repositories" (MSR 2022)
- Google Award for Inclusion Research (AIR): research project "What Causes the Lack of Diversity in Open Source?"

9.2.2 Staff hosting policy

To ensure smooth integration, the ACES team meticulously prepares for new hires. On arrival day, a team member assists newcomers with administration. For senior researchers, the team leader dispatches a communiqué detailing their expertise and research interests. New senior members present their previous work at the earliest team seminar. Junior researchers are also encouraged to share their ongoing work or analyses of publications shortly after joining.

The team also hosts invited researchers. During the reporting period, it welcomed Pierre Jouvelot (Mines Paris, long-term invited researcher), Edward Lee (UC Berkeley), Sergio Rajsbaum (UNAM Mexico), Michel Raynal (Université de Rennes I), Louisa di Felice (Universitat Autònoma de Barcelona), Sebastiano Vigna (Università degli Studi di Milano), and Hagit Attiva (Technion). It has also invited a doctoral student, Stefano Balla (Università di Bologna).

9.2.3 Success in competitive calls for projects

Team members frequently engage with local (e.g. chairs, IP Paris, IMT), national, and European project collaborations, ensuring a balance of doctoral student supervision. They work collaboratively and abstain from overlapping proposals for the same project calls. This funding approach aids in advancing research, and bolstering relations with other research institutions, industries, and services responsible for technical and digital sovereignty.

The doctoral and post-doctoral students, research engineers, and parts of the associated laboratory equipment and travel budget are financed via a variety of sources: CIFRE doctoral contracts (see section 9.4.1), industrial collaborations, such as with CEA, Digiteo, Inria, or the SEIDO common laboratory with EDF, industrial chairs (see section 9.4.1), national calls for projects (ANR, IAD/CIEDS, PTCC/Campus Cyber, PEPR ARSENE, PEPR Cybersécurité, PEPR Réseaux du futur), PhD scholarships and PhD track programs from IP Paris, grants (Nomadic Labs), or a Chateaubriand fellowship for doctoral student exchanges.

9.2.4 Equipment quality and technological skills

The team has access to laboratory resources to support its research activities. In addition to the computing resources shared with the rest of the laboratory, the team hosts and administers a server with 4 terabytes of memory used for large-graph compression and analysis. Furthermore, it has access to the Software Heritage infrastructure and datasets.

Members of the team have also developed various platforms and software, as support for their research activities and to help disseminate results and allow further experimentation. A selected set of platforms is described in section 9.3.1. These platforms are available as free software under various open-source licenses (GPL, LGPL, Eclipse Public License, BSD 2-clause). Contributions from outside members are welcome and encouraged. They are accompanied in the process as time and resources permit.

9.2.5 Synthetic self-assessment

Strengths: Team members are deeply involved in their scientific community, taking leading roles in organizing events, editing, and committee participation.

Weaknesses: The team faces challenges in maintaining continuity and support for their projects due to a shortage of research engineers and support staff.

Opportunities: The team members' notable success in disseminating research opens avenues for enhancing their reputation and attracting potential collaborations and funding.

Threats: Transition periods between projects, coupled with fluctuating team composition, jeopardize the sustainability and progress of ongoing projects.

9.3 Scientific Production

The team's scientific production and research results are mainly focused on the security and safety of distributed embedded systems and are mainly part of the "digital trust" research area of the IDIA IP Paris department. In this context, the team is addressing several topics detailed below.

9.3.1 Qualitative analysis

In this section, the team highlights the most significant outputs and underscores the scientific advancements showcased in this selection. We place particular emphasis on the top publications, predominantly from conferences A and A^* , Q1 journals, and books, demonstrating the excellent quality of these achievements. These productions are related to one or several of the five research areas: Cybersecurity, Safe and Secure Distributed Systems, Software Engineering, Embedded Real-Time Systems, and Autonomous and Energy-Aware Systems.

Cybersecurity

A first cybersecurity research line, within the joint SEIDO laboratory, aims at defining secure object management protocols. This work has resulted in two patents [42, 78]. We also developed an adversarial method for generating network packets to invalidate Deep Learning-based Network Intrusion Detection Systems in IoT [61].

Another line of research develops optimal defense strategies for critical systems through game theory. A comprehensive overview is provided in [44]. Furthermore, in the C3S chair, this has led to improved Moving Target Defense deployment strategies [903]. New approaches to modeling and solving security games were explored. In [19], *Obstruction Logics* were introduced, enabling the development of a model-checking procedure for security.

Lastly, research efforts have been directed at securing the global software supply chain, leveraging Software Heritage for free/open source components (FOSS) security. This has led to better identification of FOSS components in unknown code bases [71, 69] and detecting anomalies in open source repositories. The recently funded SWHSec project explores the potential of Software Heritage in open-source security. ACES is also active in the Reproducible Builds project with a team member on the board [48] (IEEE Software best paper award for 2022). Further ongoing work covers modeling explicit supply chain attacks [70] and exploring reproducible builds for enhanced security [50].

Safe and Secure Distributed Systems

Today's computing systems, ranging from fire alarm sensors and laptops to internet-scale services, are inherently distributed. Our research explores the fundamental and system aspects of distributed computing under fault-prone and loosely synchronous models. Addressing security, particularly against Byzantine attacks where components may be fully compromised, is vital in

open, large-scale systems. Blockchain emerges as a solution for reliable data access amidst mutual distrust, leveraging protocols such as reliable broadcast, consensus, state-machine replication, erasure coding, and zero-knowledge proofs.

We investigate the inherent drawbacks of these protocols — energy consumption, throughput, and latency — and propose methods to overcome them. Specifically, we explore the cryptocurrency (asset-transfer) challenge, aiming to develop efficient solutions that reduce the need for global synchronization. Our research has led to innovations such as a fast Byzantine consensus algorithm requiring only 5f-1 replicas [47], an accountable lattice agreement protocol [29], a scalable reliable broadcast protocol [33], a consensusless cryptocurrency prototype [46], comparative analyses of blockchains and Byzantine fault-tolerant protocols [24], as well as a concurrency-optimal solution for asynchronous asset transfer [72].

In conjunction with its focus on safety and security in distributed systems, our team also prioritizes data protection, particularly for images, against prying storage providers. Techniques include data fragmentation, encryption, and dispersion, optimizing classic secret sharing for better performance and memory efficiency with some security compromise [41, 62]. Image protection strategies involve frequency domain fragmentation and novel algorithms for reconstruction without prior knowledge [63]. Moreover, deep learning enhances these methods and proves effective in breaching systems, exemplified by attacking a network intrusion detection system with minor dataset modifications yet high success rates [61].

Software Engineering

The team’s research extends into software engineering, covering both Empirical Software Engineering (EMSE), particularly in analyzing free/open source software (FOSS) artifacts, Model-Based Systems, and Software Engineering (MBSSE) for Cyber-Physical and Embedded Systems.

In EMSE, the Software Heritage (SWH) initiative, co-founded by an ACES team member prior to joining Télécom Paris, stands out by amassing the largest public collection of software source code, with over 18 billion files and 3.8 billion commits from 280 million FOSS projects [21, 1]. Our work on SWH includes developing scalable indexing for vast version control system graphs [73] and releasing a large-scale open-source license text variants dataset, which received the best data paper award at MSR 2022 [74, 32]. Additionally, we conducted studies on the diversity of public code contributors [68, 67], recognized by the Google Award for Inclusion Research in 2022.

In MBSSE, our focus has been on rectifying design errors early in development to avoid delays, emphasizing automatic code generation from AADL models with the RAMSES platform [17], and advancing foundational aspects of MBSSE through Multi-Paradigm Modeling (MPM) techniques [6, 2, 16, 31, 15]. Our efforts also cover Model Management (MoM), focusing on model consistency management and synchronization [56, 55, 54].

Moreover, we explore formal verification of multi-agent systems, addressing the undecidability of model checking with approximations and bounded memory concepts [9, 11], as well as hybrid techniques and abstraction-refinement methods to reduce complexity [27, 28, 8]. Our research also includes applying these methods to real-world scenarios such as auctions [10, 64, 7].

Embedded Real-Time Systems

Mixed Criticality Systems (MCS) are required to manage the uncertain worst-case costs of resources, such as execution and energy, under optimistic or pessimistic estimates. High-criticality tasks run regardless of these costs, while low-criticality tasks might be scaled back or dropped in high-criticality mode to free resources for more critical tasks [52]. Our research includes developing a global static scheduler for MCS that handles task dependencies efficiently on multi-processors [52, 53], and its implementation on the Litmus-RT kernel [59]. This work aims to extend the mixed-criticality concept to other resources, enhancing energy efficiency and application to drone swarms and connected devices.

In predictable computing, the focus is on the interplay between critical real-time software and its execution platform to ensure high performance and provable WCET bounds, overcoming hard-

ware design issues that may introduce timing anomalies [13]. Our contributions include a more expressive definition of timing anomalies [13], an optimal cache model for WCET analysis [18], extensions to the TDM bus arbitration scheme for mixed-criticality systems [34, 35], and a formal framework for modeling DDR memory controllers in Coq [960].

Additionally, collaborations with Nanyang Technological University led to a survey on timing-constrained resource allocation techniques in cloud computing [65], and research on detecting instantaneous cycles in component-based simulation models to ensure sound behavioral composition [58].

Autonomous and Energy-Aware Systems

Research in autonomic systems has covered multi-scale, self-adaptive, healing, integrating, and explanatory aspects. Our contributions include identifying cross-domain theoretical principles, like multi-scale feedback design patterns [23] and self-integration, adaptation rules [12], and applying them to specific domains, such as self-adaptive vehicular networks [674] and decentralized self-healing systems [66]. This foundation aids the SmartGarden project in designing an expandable, eco-friendly monitoring system, focusing on energy and water management.

The SmartGarden project¹, involving LMD/IPP, SAMOVAR, and LTCT's ACES and SSH teams, explores the environmental benefits of urban vegetation. Its objectives are demonstrated through installing autonomous sensors in Télécom Paris gardens, supported by the E4C interdisciplinary center². This initiative aims to develop cost-effective, solar-powered measuring stations to generate and archive environmental data, optimize irrigation, and engage the community in maintenance, leveraging ACES's expertise in autonomous and energy-efficient systems. Those inexpensive stations will be benchmarked against those certified by Météo France. Environmental data will be archived in the E4C DataHub and will be used for efficient irrigation and vegetation monitoring while involving employees in garden maintenance, adding a social science aspect to enhance equipment acceptance in urban settings.

9.3.2 Potential and dissemination strategy

Publications are evenly distributed between the five themes and between junior and senior team members. Some members maintain close collaborations with renowned international researchers. Others collaborate closely with other team members. As a result, less active members become more active and contribute significantly to research.

Over the past five years, the team has welcomed Vadim Malvone, who has been shepherded by Jean Leneutre. Vadim Malvone already has a strong scientific output and is starting to publish at very prestigious conferences. Laurent Pautet has shepherded Stefano Zacchiroli, who has become a very active member of the team. Indeed, he has joined the security research area and proposed that the team collaborate on the SWHSec project. For his part, he shepherded Théo Zimmerman and Xhevahire Tërnavá.

Less active members co-supervise two PhD students each, collaborating with Laurent Pautet and Stefano Zacchiroli. Recently, they have intensified their research activities and have published in at least one journal and at one conference over the past two years. Additionally, they are deeply engaged in the team's recently started flagship projects, such as Software Heritage, Smart Garden, and PEPR projects.

Dominique Blouin, who had been a research engineer, has been promoted to "Maître de Conférences" and, because of his impressive track record, has obtained an "Autorisation à Diriger des Recherches Temporaire" as well as being authorized to supervise a PhD student. He is also involved in the supervision of two other PhD students. Three other members are about to obtain their "Habilitation à Diriger des Recherches" (HDR): Florian Brandner, Ada Diaconescu and Jean Leneutre.

¹<https://www.telecom-paris.fr/fr/ideas/smart-gardens-vegetalisation-temperature>

²E4C (Energy for Climate) is an interdisciplinary center of IP Paris with École des Ponts ParisTech, CNRS, CEA, TotalEnergies, EDF, and the SGPI.

9.3.3 Scientific integrity, ethics and open science

Some team members, such as Laurent Pautet and Samuel Tardieu, have been contributing to free software for over 30 years, in particular to the GNAT/GCC project. Others, like Stefano Zacchiroli, have been spokespersons for the Debian project and are now involved in large-scale open-source projects such as Software Heritage. Finally, others like Étienne Borde and Dominique Blouin have long been involved in the development of Eclipse technologies. The team therefore possesses an impressive open-source culture.

In addition, the team is enthusiastically involved in the interdisciplinary Energy for Climate (E4C) center, notably in the research area on energy efficiency, and has reoriented its research to apply it to the field of energy-awareness systems. Finally, the team is committed to setting up Smart Garden, one of the 6 demonstrators of the E4C living lab, the only one at LTCI, in collaboration with the LMD (Laboratoire de Météorologie Dynamique), and intends to use this demonstrator as a showcase for its research results.

The Software Heritage project (cf. portfolio) has become a pillar of open science activities in France, and has been recurrently mentioned in the French National Plan for Open Science, now in its second edition (2021–2024)³. The project has led the way to affirming open-source software and its archival as a third pillar of open science, together with open access (for publications) and open data (for experimental data).

9.3.4 Synthetic self-assessment

Strengths: The ACES team has a noteworthy record of high-quality, diverse scientific production, with contributions spanning top-tier publications, patents, databases, and open-source code. Each area of their broad research focus, encompassing core subjects such as autonomy, safety, and security, produces an impressive number of A*, A, or Q1 publications. The team's active involvement in numerous chairs, significant projects, and open-source platforms, as well as their achievement in receiving the "Autorisation à Diriger des Recherches" from École Doctorale IDIA, affirm their academic excellence. The exceptional nature of these results lies in their deviation from current trending research topics.

Weaknesses: The rapid proliferation of Artificial Intelligence (AI) in the academic sphere has resulted in less recognition for many areas of research activity, despite their critical importance in both academic and industrial research.

Opportunities: The team is poised to seize opportunities in emerging fields. Their expertise in key scientific fields will be indispensable in the future as AI and machine learning-based systems, especially those demanding compliance with safety, security, and energy constraints, see greater deployment.

Threats: The team faces threats in recruitment, particularly in the fields overshadowed by AI's allure. The exodus of young researchers to industry, coupled with the challenge of attracting PhD students and post-docs, has complicated the renewal process for excellent researchers. Smaller research communities within the ACES team also grapple with threats, such as conference rankings and evaluations that favor larger communities, leading to downgrades for top-tier conferences and previously Q1 journals marginalized by the AI boom. This situation highlights the difficult environment for conducting and promoting exceptional research in smaller communities.

9.4 Contribution of Research Activities to Society

The ACES team conducts numerous activities outside of its academic circle (Télécom Paris, IP Paris), to enable society to benefit from the most from the team research activities.

³<https://www.ouvrirelascience.fr/second-national-plan-for-open-science/>

9.4.1 Socioeconomic partnerships and interactions

Industrial Chairs

The first mechanism utilized by the team to transfer results to society at large is that of industrial chairs. The team participates in many industrial chairs, all with major industry players, and holds leadership positions (e.g. scientific responsibility) in a number of them. Below we recap the industrial chairs active during the current reporting period:

- Chaire TrustShare⁴: a blockchain-oriented innovation chair, to develop consistent and efficient data replication protocols for large-scale, dynamic environments affected by mutual distrust. The chair is financed by Mazars Group and Caisse des Dépôts, with scientific leadership from ACES member Petr Kuznetsov. Most notably, TrustShare financed the PhD work of Andrei Tonkikh and Joao Bezerra. A second iteration of the chair ("TrustShare II"), with a focus on the economic and societal aspects of decentralized finance and blockchain, is being prepared.
- Chaire IHEDN⁵: on cybersecurity and digital sovereignty, hosted at *Institut des Hautes Études de Défense Nationale* (IHEDN), in partnership with ANSSI, Sopra Steria, CEA, COMCYBER, EDF, NAVAL Group, Total Energies Group. The chair aims to contribute to the debate on digital sovereignty and cybersecurity, through multidisciplinary research at the intersection of engineering sciences, humanities and social sciences. The chair is led by ACES member Jean Leneutre.
- Chaire ISC⁶: about the engineering of complex systems, sponsored by Thales, Dassault Aviation, DCNS, and DGA and co-led by ACES member Laurent Pautet on behalf of ΣΚΦ.
- Chaire ASC⁷: on the architecture of complex systems, financed by Dassault Aviation, Dassault Systèmes, Naval Group, Nexter, and AID (*Agence de l'Innovation Défense*) and co-led by ACES member Laurent Pautet on behalf of ΣΚΦ.
- Chaire C3S⁸: on connected cars and cybersecurity, financed by Nokia, Renault, Thales, Valeo, and Wavestone.
- Chaire CyberCNI⁹: on the cybersecurity of critical networked infrastructure, financed by Airbus, Amossys, BNP, EDF, Nokia, and SNCF.

Joint Laboratories

Joint laboratories between academia and industrial partners provide another opportunity to cross-pollinate research and society at large. The team is active on this front, most notably with Jean Leneutre, who since December 2023 co-supervises the SEIDO¹⁰ (*SEcurité et Internet Des Objets*) joint laboratory that gathers research scientists from both academia (Télécom Paris, Télécom SudParis, Mines Saint-Étienne and CNRS LAAS) and industry (EDF R&D) with multidisciplinary expertise and skills (energy, security, communication networks, etc.).

SEIDO aims to contribute to the design of large-scale, distributed computing architectures capable of monitoring and managing power distribution systems up to terminal equipment, including local generation and decentralized storage, to contribute to the achievement of new concepts, new standards for the definition of new equipment, and new software and thus develop a common intellectual legacy.

⁴<https://trustshare.telecom-paris.fr/>

⁵<https://cyber-ihedn.fr/>

⁶<https://225.polytechnique.fr/225-histoires/chaire-systemes-complexes.html>

⁷<https://rb.gy/abdliu>

⁸<https://chairec3s.wp.imt.fr/>

⁹<https://cybercni.fr/>

¹⁰<https://seido-lab.com>

CIFRE Theses

The financing of CIFRE PhD theses is a third way to encourage interactions between academia and industry, that the team pursues actively. The following PhD students have been financed by CIFRE theses during the reporting period:

- Florient Champenois (supervised by Florian Brandner): CIFRE with Safran R&D Massy, to develop a new kind of real-time network organization for (small) aircraft and tools to ensure safety/timing guarantees.
- Maxence Brugères (supervised by Petr Kuznetsov): CIFRE with Mazars Group, on the topic of privacy and anonymity in large-scale distributed systems, with a focus on secure auditing.
- Sameh Khalfaoui (supervised by Jean Leneutre and Pascal Urien): CIFRE with EDF R&D, to develop secure zero-trust bootstrapping mechanisms for IoT.
- Gabriel Ballot (supervised by Jean Leneutre and Vadim Malvone): CIFRE (started in October 2022) with EDF R&D, to provide methods, models, and tools to enable the definition and implementation of active defense strategies tailored to the context of IoT.

Environment and other Major Societal Challenges

Some of the research projects of the team are intended to have direct, positive impact on major challenges of our time, such as the SmartGarden project described in section 9.3.1.

More generally, the team is active in the reflections on the evolution and impact of technology on individuals, society, and the environment. Ada Diaconescu’s work on this front resulted in several publications on topics that include: the environment [14], social values [22], the governance of socio-technical systems [60], and privacy [51]. These topics have also been presented to Télécom Paris students (both initial and continuing education) in numerous occasions, e.g. with classes on the ethics of AI.

Cultural Heritage

The team is also active in other areas of society. Most notably in the cultural sphere, the Software Heritage project, in partnership with UNESCO¹¹, co-founded and led by ACES member Stefano Zacchiroli, works toward the goal of preserving all software available in source code form for future generations. UNESCO’s interest in the project resides in the fact that software source code contains invaluable information *for humans*, and not only machines: software source code embodies precious technical knowledge, which is part of the broader technical and cultural heritage of humanity.

This line of work resulted in the publication of the Paris Call for Software Source Code as Heritage, released in 2019¹².

Continuing Education

Recognizing the important role in society of continuing education, the team is very active on this front, most notably with several team members acting as (co-)coordinators (*responsables pédagogiques*) of post-master’s degree programs (*Mastères Spécialisés*, or MS) offered by Télécom Paris¹³:

- MS on Information Systems Management, in partnership with ESSEC business school, coordinated by Stefano Zacchiroli (previously by Sylvie Vignes)
- MS on Cybersecurity and Cyberdefense, coordinated by Thomas Robert
- MS on Embedded Systems, coordinated by Florian Brandner

¹¹<https://www.softwareheritage.org>

¹²<https://en.unesco.org/foss/paris-call-software-source-code>

¹³<https://www.telecom-paris.fr/en/post-masters-degree/all-post-masters-degree>

- MS on Enterprise Digital Architecture, coordinated by Mounira Msahli
- MS on Design, Network Architecture, and Cybersecurity, coordinated by Mounira Msahli

Education Management

The team is also active in the broader context of education in France. At the national level, team member Samuel Tardieu is a member of the National Council for Higher Education and Research (*Conseil National de l'Enseignement Supérieur et de la Recherche*, or CNESER) and of the Higher Council of Education (*Conseil Supérieur de l'Éducation*, or CSE).

9.4.2 Research valorization and transfer

The team pursues research valorization via two main mechanisms: patents and the definition of international standards.

Patents

ACES team members have authored several patents, to transfer research results to concrete innovation that society can benefit from:

- As part of his PhD work, Sameh Khalfaoui (supervised by Jean Leneutre and financed in the context of the SEIDO joint laboratory) proposed a hybrid secure device pairing scheme leveraging cryptographic techniques and physical layer properties to establish a secure connection between devices. The result of this work has been patented, in both France and Europe at large [42].
- As part of the same PhD work they designed an enrollment protocol based on physically unclonable functions (PUFs) that is resistant to insider threats using machine learning watermarking techniques. The corresponding process has been patented in France [78] and underwent a technology transfer as part of an operational project at EDF.
- Florian Brandner, Laurent Pautet, et al. work on the time-division multiplexing of concurrent access to resources [36] has been patented in France and filed for patent in the US [40, 37]
- As part of his PhD work, Florient Champenois filed a patent on computing the worst transmission time in distributed networks for avionics certification, with Florian Brandner et al. [20].

Standardization

The team is also active in standardization activities, intending to facilitate technical interactions in society among independent stakeholders. In the reporting period, ACES team members have worked on the following international standards:

- Laurent Pautet, Étienne Borde, and Dominique Blouin actively participate in the working group of AADL (Architecture Analysis and Design Language), an SAE international standard¹⁴. In addition to regular participation in the group activity, Étienne Borde has contributed the behavioral model annex for the AADL V2 standard, as well as acting as an editor for it.¹⁵
- Mounira Msahli has coauthored with colleagues from Télécom Paris as well as Cisco, and Qualcomm, IETF RFC (Request For Comment) 8902¹⁶, proposing a TLS extension (and experimental implementation of it) to support IEEE/ETSI certificate types to authenticate entities.

¹⁴<https://www.sae.org/standards/content/as5506c/>

¹⁵<https://mem4csd.telecom-paristech.fr/blog/index.php/aadl-ba-frontend/>

¹⁶<https://datatracker.ietf.org/doc/rfc8902/>

- Stefano Zacchiroli is co-leading the working group for the ISO open standardization of SWHIDs¹⁷ (SoftWare Hash IDentifiers): intrinsic, cryptographic secure identifiers for the source code artifacts (individual files, source trees, commits, releases, etc.), already used as a *de facto* standard by Software Heritage, the SPDX ISO standard¹⁸, and Wikidata.

9.4.3 Science popularization

Team members were also engaged in science popularization activities during this reporting period. Various teaching activities for a non-academic public were pursued. Together with Jet Brains, Petr Kuznetsov organized three editions of the School on Practice and Theory of Distributed Computing (SPTDC)¹⁹, open to the general public. He also co-authored a technical book on algorithms for concurrent systems [45].

Samuel Tardieu co-authored a publicly available MOOC course on how to build a compiler²⁰. We also participated in webinars for different audiences, including continuing education students. Florian Brandner presented, together with other post-master degree teachers, the webinar "*Métiers dans l'industrie de l'embarqué: les compétences recherchées du futur*".

Team members are sporadically active in the media. For example, Stefano Zacchiroli co-authored [57] a *Le Monde Diplomatique* article on the state of open source as a digital commons. On a related topic, the relationship between open source and the state, he was interviewed by the *Conseil National du Numérique* and *Le Monde*²¹. He also participated in radio interviews about his work on the lack of diversity in open source²².

Some team members also contribute to Télécom Paris Ideas²³, a recently launched magazine by Télécom Paris to debate socio-technological topics. Laurent Pautet and Ada Diaconescu have contributed an article²⁴ about the SmartGarden project, whereas Stefano Zacchiroli was interviewed for a podcast episode about digital commons and free software²⁵.

9.4.4 Synthetic self-assessment

Strengths: The team excels in external engagement, demonstrating leadership in industrial chairs, joint laboratories, and notable involvement with non-tertiary education programs, including specialized masters. Their active role in setting international standards, securing patents, and maintaining a vocal presence in societal debates highlights their influential position in discussions on green transition, AI ethics, digital sovereignty, and techno-cultural heritage. A significant strength is their commitment to open science and open source, which not only fosters transparency but also amplifies their research's impact across various fields.

Weaknesses: The relative underutilization of CIFRE theses highlights an area for growth, despite the team's access to alternative industrial funding for PhDs. Additionally, activities around startup support and technology transfer are noted to be minimal, partly because current industry transfer models clash with the team's open research ideals. This misalignment suggests a need for innovative approaches to reconcile these differences.

Opportunities: The team has a unique opportunity to redefine industry collaboration through its strong advocacy of open science and open source. By pioneering business models that harmonize with open research, they could set new standards for technology transfer, potentially revolutionizing how academia and industry collaborate. Expanding efforts in science popularization, leveraging their commitment to openness, could further bridge the gap between research and the public, fostering greater societal engagement and understanding.

¹⁷<https://www.swhid.org/>

¹⁸<https://spdx.dev/>

¹⁹Last edition (2023): <https://lp.jetbrains.com/sptdc-2023/>

²⁰<https://compilation-course.github.io/>

²¹<https://rb.gy/w11jve>

²²<https://rb.gy/fex31v>

²³<https://www.telecom-paris.fr/fr/ideas/>

²⁴<https://www.telecom-paris.fr/fr/ideas/smart-gardens-vegetalisation-temperature>

²⁵<https://www.telecom-paris.fr/fr/ideas/communs-numeriques-logiciels-libres>

Threats: The current industry transfer norms, which often emphasize exclusivity and proprietary outcomes, pose a potential threat to the team's ethos of open research. This could limit their willingness to engage in certain technology transfer activities. Additionally, the challenge of allocating time effectively between academic responsibilities and the desire to popularize science might hinder their ability to fully engage with the wider community, despite recognizing its importance.

Chapter 10

Self-assessment of C2 team

10.1 Profile, Resources and Organization

10.1.1 Scientific objectives

The C2 team is dedicated to research in the following areas and the interactions between them:

- Cryptography
- Cybersecurity
- Fundamental research

The interconnection between cryptography, cybersecurity, fundamental mathematics and theoretical computer science is both profound and essential. Cryptography relies on mathematical concepts such as algebraic structures, modular arithmetic, and combinatorics for its design. These algorithms form the foundation of cybersecurity, which, along with other practical techniques, encompass a broad range of measures aimed at safeguarding digital security from unauthorized access, data breaches, malware attacks, and other cyber threats. Based on this interconnection, the LTCI decided to regroup the MC2 and CCN teams to develop this vision for a long-term project, with evident interactions with other teams working on security at the school, such as SSH and ACES. Our objective is to develop research in all three areas: cryptography, cybersecurity, as well as fundamental research with regard to their interaction.

In the following, we give some concrete projects.

Cybersecurity

To address the vast and disparate group of interconnected networks and devices, it is necessary to implement tailored security and confidentiality systems, where underlying mechanisms are closely related to the services involved. Security requirements may vary considerably depending on the services offered.

We work on tailored approaches to security that can meet a broad range of security requirements, and to provide adaptive security systems. Such systems address multiple operational and environmental constraints while taking into account the following properties: flexibility, lightness, autonomy, mobility, and interoperability.

Aiming to provide defense against a high number of critical attacks, the challenges that we address are: adaptive end-to-end security architectures with lightweight and scalable security functions and protocols, scalable trust management with lightweight cryptographic functions/mechanisms and crypto-agility, identity management and lightweight authentication mechanisms, and blockchain-based solutions for cybersecurity mainly for access control, integrity, and resilience. These application fields can be found in several collaborative research activities split into three topics: security

and trust in information and networking systems, attack analysis, and misbehavior detection and privacy.

Our future research projects mainly strengthen the aforementioned activities with new areas such as privacy models, blockchains, and protocols for Time Sensitive Networking (TSN), in particular:

- Trusted and secure communications in scalable and constrained environments.
- Security data analytics in large-scale networks/systems.
- Attack analysis and countermeasures in information networks.

Cryptography

With data now being extensively stored in the cloud, users also need to trust the cloud servers/authorities that run powerful applications. As privacy becomes an increasingly important issue, new techniques should be developed to protect personal information and to reduce the requirement for trust in the authorities, in particular in the context of computing encrypted data. In all these situations, the typical one-to-one communication should be generalized to one-to-many or many-to-many communication. In such multi-user settings, it is necessary to address the collusion of different parties whose aim is either to breach privacy or to deter the resulting computation. This requires us to define new notions of security, sometimes very disputable ones (many current works deal with new concepts to define the meaning of the right to be forgotten, [GGV20] as the users' information is not only stored in the database but also used in many applications, or the traceability of personal data, for instance). A large number of advanced cryptographic primitives have been introduced to guarantee the aforementioned security goal in this fascinating movement of technologies.

Our research projects aim to introduce new tools and techniques to address cryptographic questions arising from new technologies such as cloud services or big data, and against strong adversaries. The two following research lines provide our team's main focus:

- Decentralized cryptography to enhance privacy (by reducing the need for trust in the authorities e.g. cloud servers). The objective is to decentralize computations in protocols that process data supplied by multiple distrustful parties, to meet the security and privacy requirements brought about by emerging applications.
- Algorithmic tools for advanced post-quantum cryptographic primitives. This line of research will be mainly developed to introduce algorithmic problems and investigate their hardness for the design of concrete primitives.

Some specific projects:

- Decentralized cryptography and database privacy.
 - Decentralized FHE in multi-user settings.
 - Decentralized functional encryption with traceability.
 - Tools for distributed computation on secrets with perfect security.
 - New functionalities in advanced primitives.
 - New attack model and countermeasures.
 - Machine learning over encrypted data.
- Digital signatures and their applications to consensus.
- Post-quantum security. The American National Institute of Standards and Technology (NIST) has announced its first set of standards for post-quantum cryptography, including three lattice-based schemes and one hash-based scheme. For the moment, all these lattice-based schemes lack security proof based on the hardness of worst-case lattice problems. The main lines of research will be to investigate whether the worst-case connection can be established or better

attacks can be designed for these lattice-based standards. Another important objective is to investigate the quantum security of these lattice-based schemes. So far, little is known today about the quantum security of lattice-based systems, beyond the absence of knowledge about efficient quantum attacks. Overall, in the next 5 years, we aim to have a better understanding of the security of these lattice-based post-quantum cryptographic standards.

- Symmetric cryptography. We will mainly explore the following lines of research:
 - Propose new ML-based algorithms to analyze classical cryptographic problems, such as learning parity with noise (LPN) problems or others.
 - Propose new post-quantum digital signatures based on a one-way function, targeting a short signature size and a high speed.
 - Propose new hash functions friendly for secure multi-party computation (MPC) applications.
 - Propose new symmetric key primitives friendly for transcribing homomorphic encryption (HE).

Fundamental research

We traditionally conduct research activities in fundamental mathematics — algebraic geometry, number theory, and combinatorial coding theory — as well as in areas at the frontier between discrete mathematics and computer science — automata, coding theory, cryptography, and computational complexity — but still with a predominantly mathematical perspective. Recent work has been carried out on the following topics.

- In algebraic geometry, projects are chosen first for their intrinsic mathematical interest, and also for their applications in theoretical computer science and information theory, in coding theory, combinatorics, complexity, computability, or cryptography. Combinatorial coding theory being one source of methods for coding theory, we explore this theme through Boolean functions and cryptography, minimal codes, and their variants, as well as zero-error information theory and extremal combinatorics.
- In graph theory, we study several variants of the dominating set problem, and more precisely the notions of locating-dominating codes and identifying codes. The combinatorial properties of these objects are studied as well as the complexity of certain related optimization problems. In a second field in which our former team (MC2) is a pioneer, problems related to complexity theory are explored, including the study of median orders and the uniqueness of optimal solutions in classical problems in addition to the complexity of the decision for the existence of a unique solution. Some of these problems do not fall under the usual complexity classes, e.g. NP , but higher in the polynomial or Boolean hierarchy, such as $\Theta_2, \Delta_2, F\Delta_2, DP$ classes.

We can identify the following three structuring themes, further developing our past research activities as well as interactions with the team's new research directions.

New interfaces in coding theory. Coding theory is historically the team's flagship topic, which was initiated by former members Gérard Cohen and Gilles Zémor. In coding theory, our interest lies mainly in "non-classical" problems, in the sense that they depart from the usual questions of minimization of the error rate and the practicality of decoding. A sample of the topics we are working on is:

- Study of new classes of codes motivated by specific applications to the storage of secrets (locally decodable codes, private information retrieval, regenerating codes) and other applications (broadcast etc.)
- New constructions of rank-metric codes, potentially from AG curves.
- Study of codes as abstract mathematical objects (algebraic, combinatorial, geometric, or metric properties etc.)

- Application of methods from coding theory to other branches of mathematics.
- Construction of code-based cryptosystems resisting quantum attacks. This line is actually well studied by the team, e.g. a proposal of the first code-based identity-based encryption in CRYPTO '17.

New problems in complexity theory and in graph combinatorics Finally, in graph theory, one of our main themes is the study of identifying codes and related problems. The team has already obtained numerous results concerning this topic in the past, which we plan to study further; but it has also enabled the introduction of new questions in complexity theory, such as the complexity of decisions for the existence of a unique solution. This last question seems very natural and fundamental, and studying it in a more general setting should open up a promising new line of research for us.

10.1.2 Resources

Team leader: Duong Hieu Phan, Professor

Faculty:

- Hassane Aissaoui, Research Engineer
- Patrick Bellot, Professor (retired in 2023)
- Sébastien Canard, Professor
- Victor Dyseryn, responsible for digital training of future civil servants in the "Corps des mines"
- Olivier Hudry, Professor
- Rida Khatoun, Professor
- Houda Labiod, Professor (on leave since 2021)
- David Madore, Associate Professor
- Bertrand Meyer, Associate Professor
- Matthieu Rambaud, Associate Professor
- Jacques Sakarovitch, Emeritus Professor
- Ahmed Serhrouchni, Emeritus Professor
- Pascal Urien, Professor
- Qingju Wang, Chair of Junior Professor
- Weiqiang Wen, Associate Professor

Associated Professors: Katarzyna Kapusta, Antoine Lobstein, Sihem Mesnager, Hugues Rindriambololona, Damien Stehlé.

PhD Students: Elloh Adja, Ferran Alborch, Rita Azzi, Edouard Bochet, Mohammed Bouchouia, Safa Boudabous, Antoine Boudermine, Emma Braïteh, Orel Cosserson, Zakarya Drias, Charles Dubos, Achraf Fayad, Abdessamad Fazzat, Karolina Gorna, Jean-Jacques Grund, Pengwenlong Gu, Farah Haidar, Mohamed Tahar Hammi, Joseph Kamel, Sameh Khalfaoui, Sleiman Koueik, Hao Lin, Zepeng Liu, Hortense Maigne, Estelle (Sylvain) Marie, Jean-Philippe Monteuuis, Ismet Kerenciler, Dinh Duy Nguyen, Nathan Papon, Ky Nguyen, Édouard Rousseau, Angelo Saadeh, Antoine Urban, Ayoub Wehbe, Zhenzhe Zhong.

Post-docs: (TBC) Fadlallah Chbib, Ali El Attar, Pengwenlong Gu, Badis Hammi, Hamza Khemissa, Christophe Levrat, Liam Matthew Medley, Jun Zhan.

10.1.3 Human resources management, safety, environment, ethical protocols, data and scientific heritage protection

The C2 team hosts regular seminars and reading groups that also draw the participation of researchers and PhD students from various groups at Institut Polytechnique de Paris (such as ComNum, Inria Saclay, and Télécom SudParis).

10.1.4 Synthetic self-assessment

Strengths: With the rapid advancement of technology, the demand for security in cloud computing and big data is exceedingly high and will continue to grow in importance. Our team comprises very active, relatively young members covering all relevant topics of cryptography and privacy, with a solid background in mathematics, benefiting from the valuable assistance of team members working on fundamental tools.

Weaknesses: Several members of the cybersecurity team (CCN team), including Houda Labiod, Ahmed Serhrouchni, Patrick Bellot, have either left or retired. It is essential to hire new active members to strengthen the cybersecurity team and foster multiple ongoing collaborative projects with industry.

10.2 Attractiveness

10.2.1 Scientific reputation and contributions

In Cryptography:

- Program Chair of SCN conference, an important cryptography and security conference (second only to Eurocrypt in Europe): <https://scn.unisa.it/scn24/index.php/call-for-papers/>
- Member of "Comité de pilotage" of GT C2 (Coding and Cryptography) of GDR Sécurité Informatique <https://crypto.di.ens.fr/c2:main>
- Area Chair of Asiacypt - one of the three flagship conferences in cryptography <https://asiacrypt.iacr.org/2023/callforpapers.php>
- General Co-Chair of AsiaCCS - the most important cybersecurity conference in Asia <https://asiaccs2025.hust.edu.vn/organization/>
- Main organizer of IACR-VIASM Summer School on Cryptography <https://viasm.edu.vn/en/hdkh/IACR-VIASM-School-2022>
- Member of IACR Asiacypt's Steering Committee <https://www.iacr.org/meetings/asiacrypt/sc.html>
- Participation in PC of all the three flagship IACR conferences (Crypto, Eurocrypt, Asiacypt)
- Invited Plenary Speaker at "Journées Nationales 2023 du GDR Sécurité Informatique" <https://gdr-secu-jn2023.sciencesconf.org/program/>

In Cybersecurity:

- Co-Editor/co-Chair of 4 IEEE conferences (MobiSecServ 2019, 2020, 2022, 2023)
- 4 keynotes (in IEEE conferences), 2 tutorials (3H), invited talks at AMUSEC 2023 (Marseille) and CSAW EUROPE 2023 (Valence)
- 2 presentations at ETHCC, multiple communications at the IETF
- Participation in the C3S research chair (Renault and automobile manufacturers) and in the SEIDO joint laboratory (EDF)
- Co-management of the Ethertrust.com startup

In Theory:

- IFIP Vice-President (International Federation for Information Processing) and French Representative to IFIP
- Steering Committee of Latin America Theoretical Informatics Conference (LATIN)

10.2.2 Staff hosting policy

Working in the broad area of cryptography, the team is called upon to get to grips with the most pertinent issues in the field. We therefore implement a policy of inviting visiting professors (each term lasting for 3 years and renewable) specialized in the most crucial lines of research currently shaping the field's future. Damien Stehlé, a co-author of two selected NIST post-quantum standardizations on encryption and signature, has joined us to collaborate on post-quantum cryptography and fully homomorphic encryption. He is involved in PhD co-supervision with Duong Hieu Phan and also teaches second-year students. Hugues Radriam, from ANSSI who assists us in understanding the French government's perspective on developing cryptography, and Sihem Mesnager, a top expert on Boolean functions and symmetric cryptography, continue to be associated with us. This blend of complementary expertise and long-term collaborations enables our team to stay ahead in numerous research areas.

10.2.3 Success in competitive calls for projects

- Crypto: PEPR Secure Compute, BPI Visioconfiance, ANR TRUST, Beyond 5G, PhD grants and post-doc fellowship from IP Paris competition, Cifre PhD program with Orange
- Cybersecurity: Chaire Connected Cars; European Commission with InDiD (H2020), SCOOP-Part 2 (INEA-CEF/H2020), C-ROADS (INEA CEF / H2020), INTERCOR (INEA-CEF/H2020); Industrial projects (with IRT SystemX, Orange, Ministère de l'Environnement (AFIMB), Ministère de l'Intérieur), BPI PSPC SECPB2 (PIA - PSPC-Régions 2019), SNCF MOBILITES; CIFRE PhD program with ORANGE, Peugeot Citroën Automobiles, RENAULT, EDF R&D, NAVAL GROUP, Ministère des Armées, LEDGER
- Theory: ANR MANTA, PhD grants from Fondation Sciences Mathématiques de Paris IDF and from COMUE UPSay, Marie Curie fellowship
- PhD grants and post-doc fellowship from IP Paris competition,
- Cifre PhD program with Orange on Differential Privacy
- Co-coordination with LMF (Paris Saclay) in working group COFFY – CryptOgraphy & Formal method For privacY, financed by Labex DigiCosme
<https://digosme.cnrs.fr/2021-coffy-cryptography-formal-method-for-privacy/>

10.2.4 Synthetic self-assessment

We have achieved significant success in securing funding for various projects, including European, national, fundamental, industrial, and governmental calls.

The Cryptography research area has been completely reassembled with the hiring of two professors (Duong Hieu Phan in 2020 and Sébastien Canard in 2023), an assistant professor (Weiqiang Wen in 2022), a CPJ (Chair of Junior Professor; Qingju Wang in 2023), and a research scientist responsible for the digital training of future civil servants at the "Corps des mines" (Victor Dyseryn in 2023). In a field that struggles to attract experts (many researchers from other leading academic teams have left to take up positions in the industry), we successfully attract excellent researchers from both academia and industry, in France and from abroad. We also attract outstanding PhD students and post-docs, and we foster joint PhD co-supervision arrangements with prestigious academic partners (such as ENS Ulm and ENS Lyon) as well as industry partners (such as Orange).

10.3 Scientific Production

10.3.1 Qualitative analysis

Cryptography

Our research covers the mainstream topics in cryptography:

- Advanced cryptographic primitives, with the arrivals of Duong Hieu Phan in 2020 and Sébastien Canard in 2023. We are a leading team in this field, pioneering two new research areas alongside the development of new constructions for various well-established primitives. Our work has been published at top conferences, including Crypto, Eurocrypt, Asiacrypt, PETS, and PKC. In particular:
 - Decentralized functional encryption: introduced this primitive at Asiacrypt '18 then developed it at CRYPTO '20, Asiacrypt '22, and Asiacrypt '23
 - Anamorphic cryptography: introduced the notion at Eurocrypt '22 then developed it at CRYPTO '23, and PETS '23.
 - Practical applications: Contact tracing at Asiacrypt '20, Voting System at PKC '20, Attribute-based signature at PKC '24.

Our purpose is to provide both new theoretical results and practical outcomes for several specific use cases, based on our relation with our industrial partners through CIFRE PhD theses or collaborative projects.

- Post-quantum cryptography, with the arrival of Weiquang Wen in 2022. In addition to our research work on quantum-resistant advanced primitives, in relation with the previous topic, we are specialized in establishing worst-case connections and providing security analysis for practical lattice-based schemes. Firstly, in the *Journal of Cryptology* (2023), we managed to develop several worst-case connections for practical lattice-based schemes using small parameters. Secondly, at Crypto 2022, we provided concrete attacks on the lattice-based schemes in real-world settings where the leakage of secret key information is taken into consideration. The residual security of the lattice-based systems with partial key exposure is clearly captured for the first time. On the other side, at PKC '23, we also developed a more efficient transformation from interactive zero-knowledge to a non-interactive variant considering the presence of a quantum adversary.
- Symmetric cryptography, with the arrival of Qingju Wang in 2023. This enables us to develop a comprehensive overview of cryptography and to consider new interactions between our different topics. Here are some further details.
 - Design ZK-friendly hash functions. Zero-knowledge (ZK) applications form a considerable group of use cases in modern cryptography, in particular in our first topic on advanced cryptographic primitives. For many of these applications, cryptographic hash functions are used as the main building blocks, and they often dominate the overall performance and cost of these approaches. However, classical designs such as SHA-3 and several designs based on AES, become bottlenecks in the entire proof system. We co-designed a new hash function, GRIFFIN, to provide security and better efficiency in the target applications. GRIFFIN has found its application in many ZK proof systems, for example, it was directly integrated into Facebook's project Winterfell. This result is published in Crypto 2023.
 - Algebraic attacks on transciphering for approximate FHE. We focus on studying established algebraic attacks typically defined over fields and the extent of their applicability to symmetric primitives defined over the ring of integers modulo a composite q . Based on our analysis, we present an attack on full Rubato, a family of symmetric ciphers proposed at Eurocrypt 2022, designed for use in a transciphering framework for approximate fully homomorphic encryption (FHE). We show that at least 25% of the possible choices for q satisfy certain conditions that lead to a successful key recovery attack with complexity significantly lower than the claimed

security level for five of the six ciphers in the Rubato family. This result was published at Crypto 2023.

- Algebraic attacks on symmetric-based post-quantum digital signatures. Picnic is a NIST PQC Round 3 Alternate signature candidate that builds upon symmetric primitives following the MPC-in-the-head paradigm. Recently, researchers have been exploring more secure/efficient signature schemes, from conservative one-way functions based on AES, or new low-complexity one-way functions such as RAIN (CCS 2022) and AIM (CCS 2023 and Round 1 Additional Signatures announced by NIST PQC). The signature schemes based on RAIN and AIM are currently the most efficient among MPC-in-the-head-based schemes, making them promising post-quantum digital signature candidates. We present algebraic attacks on round-reduced RAIN and Full AIM-III. This result is published in Asiacrypt 2023.

Cybersecurity

Intelligent Transportation Systems (ITS) play an increasingly important role in the development of smart cities. However, with the rise of these technologies, cybersecurity risks also increase. Malware, such as ransomware, unauthorized remote vehicle control, and also botnets, can compromise the security and reliability of ITS systems, leading to potentially serious consequences for citizens and ITS infrastructure. Over the next four years, our focus is on studying and analyzing an innovative approach based on advanced algorithms inspired by artificial intelligence (AI) to detect and analyze malicious code behaviors in the context of connected vehicles. We have used advanced algorithms such as deep neural networks and decision trees, among others, to build models capable of detecting malicious behaviors with high accuracy using dynamic analysis, memory analysis, and correlation analysis between different parts of the binary code. These analyses can identify issues such as buffer overflows, code injections, encryption flaws, configuration errors, etc. Our objective was to develop early detection mechanisms for malicious code, as well as in-depth analysis tools to understand their functioning and interactions within the ITS ecosystem. It is important to mention that the code analysis algorithms mentioned above can also be used in other domains, such as blockchain, to detect vulnerabilities in smart contract codes to identify security flaws, programming errors, and potential vulnerabilities. This helps strengthen the trust and reliability of smart contracts by ensuring their correct and secure operation. A PhD thesis is currently underway on this topic. This research area is developed by Rida Khatoun.

Another part of our research activities, carried out by Pascal Urien over the period, focuses on three areas: blockchain security, IoT security, and finally the security of vehicular networks and new-generation vehicles.

- Research in the field of vehicular networks applied to the detection of malicious behavior and the security of inter-ECU communications.
- Regarding blockchain, research focused on the security of certain crypto wallets (crypto terminal) requiring proof of software integrity (i.e. attestation at run time) and physical integrity (dynamic PUF).
- We have developed the concept of the Internet of Secure Elements (IoSE), which creates high-security servers based on secure element (SE) servers for IoT environments but also for cloud platforms.

Dissemination activities are carried out by writing IETF and IRTF drafts, participating in industrial conferences such as ETHCC (Ethereum Community Conference), and delivering keynotes, tutorials, as well as demonstrations (for example at both IEEE and CES2019).

Fundamental Research

Part of the recurrent research activities of Olivier Hudry and Antoine Lobstein is concerned with the theory of the algorithmic complexity of problems. This field aims to qualitatively characterize the difficulty encountered when solving a problem, especially in combinatorial optimization.

The usual complexity classes are P, NP and co-NP (the possible equality between P and NP is considered as one of the fundamental problems of mathematics and theoretical computer science today). Despite its pertinence, our work focuses on a theme that remains seldom explored: the problem of uniqueness. Here, we not only consider the existence of a structure defined by certain combinatorial properties (for example, the structure of Hamiltonian cycles in a graph), but we ask whether such a structure if it exists, is unique or not. Apart from some remarkable results (notably concerning the "Travelling Salesman Problem" in combinatorial optimization), the literature offers few results of this nature, probably because it is thus necessary to leave the classes P, NP and co-NP in order to explore higher level classes in polynomial or Boolean hierarchies. Within this framework, we are interested in uniqueness for the following problems in graph theory: edge covering by vertices, domination, identifying codes, locating-dominating codes, coloring, Hamiltonian cycles, and chains. We have shown (see bibliographic references) that these uniqueness problems are polynomially equivalent to the uniqueness problem derived from the classical "Satisfiability" problem (SAT) in logic. As a consequence, these problems are NP-difficult but belong to the DP class (also referred to as BH2 in the Boolean hierarchy), a class that is usually conjectured to be a strict superset of $NP \cup co-NP$ and a strict subset of the class Θ_2 , also noted L^{NP} . Additional studies completing our research activities are, on the one hand in conjunction with the combinatorial aspects of identifying codes in graph theory, and on the other concerned with the application of combinatorial optimization methods to some operational research problems.

Another fundamental research activity with applications in cryptography in our team comes from associated members, in particular Sihem Mesnager, whose research work is devoted to mathematics for protection information theory. More specifically, symmetric cryptography and coding theory. Some current works in symmetric cryptography focus on the algebraic study (e.g. existence, characterization, construction, classification, enumeration, etc.) of functions defined in finite fields (in any characteristic) satisfying the properties needed for the security of the ciphers using them. For example, highly nonlinear functions play a crucial role in protecting cryptographic systems against certain fundamental attacks such as linear cryptanalysis. Other recent works are devoted to the algebraic construction of families of optimal linear codes for various applications. In particular, the design of (almost) optimal codes for direct sum masking to protect the sensitive data stored in registers against both side-channel attacks and fault injection attacks (which today are important cryptanalysis methods about the implementation of block ciphers, and which represent huge threats), optimal codes for modern distributed storage systems and suitable codes for secret sharing and also for secure two-party computation. Her recent achievements used the theory of finite fields, discrete Fourier transformation, exponential sums, tools from arithmetic and number theory, algebraic curves, and objects of finite geometry.

10.3.2 Synthetic self-assessment

We have assembled a very strong team working on all areas of cryptography (advanced primitives, post-quantum cryptography, symmetric cryptography), in addition to being pioneers in several contemporary lines of research, such as advanced cryptographic primitives (with decentralized functional encryption) and privacy (with anamorphic cryptography). We consistently publish at prestigious cryptography and privacy conferences such as Crypto, Eurocrypt, Asiacrypt, PKC, PoPETS.

10.4 Contribution of Research Activities to Society

Regarding cryptography, the impact of our research on society is major. In particular, our research strongly focuses on protecting individuals, as it explores (post-quantum) cryptographic tools dedicated to the (long-term) protection of individual privacy. Indeed, thanks to our research, users can securely access their usual services while protecting their data. In a nutshell, the technology provided by our research on advanced cryptographic primitives and post-quantum cryptography aims to dispel any doubts or distrust from end-users about the security and trustworthiness of the

technology itself, for today and also for tomorrow.

Additionally, the cryptographic technology we develop permits governmental organizations to benefit from standards that will serve as references when validating a vendor to conduct a service that may have an impact on national security. In particular, the GDPR strengthens the legal requirements for the protection of natural persons in the processing of personal data. Among the new objectives set by this Regulation, Article 25 is dedicated to "data protection by design and by default". It requires the implementation of appropriate technical and organizational measures. To enable protection by design, society must guarantee the security of the information and the respect for the rights of the persons, in particular with the minimization and the confidentiality of data. Cryptography is therefore best suited to fulfill all these requirements, thanks to tools such as encryption or anonymous authentication that we are developing.

10.4.1 Socioeconomic partnerships and interactions

In cryptography, we have established several socio-economic partnerships and interactions with industry. We currently have one CIFRE PhD thesis with Orange focused on privacy-preserving cryptography, and applications of both encryption and anonymization techniques. We are also involved in several collaborative projects with industrial partners.

- The BPI VisioConfiance (with Secure-IC and Apizee) aims to provide a secure, sovereign real-time collaboration platform. We are developing innovative security building blocks enabling end-to-end encryption of the data exchanged during collaboration sessions, as well as enhanced management of access control to data, encrypted based on attributes linked to users. Our role is to lead the research activities on cryptographic encryption primitives for end-to-end security. We have hired two PhD students as part of this project.
- The ANR TRUST (led by Orange) works on the implementation of various security and privacy-preserving measures to protect personal data to comply with regulations such as the GDPR, as well as upcoming legislation such as the "Data Act" and the "Data Governance Act". As a follow-up of the PhD thesis with Orange, our role is to appropriately combine cryptographic and anonymization techniques.
- Through the participation of Télécom SudParis, we are also indirectly participating in ANR PRESTO (led by ENS, with Orange and 6cure as industrial partners), whose purpose is to provide privacy to end-users while allowing traffic monitoring (to detect attacks or abnormal traffic) by a network security manager. Télécom SudParis is working on the network security manager part (based on its work on cybersecurity) while we provide our expertise on advanced cryptographic mechanisms. Télécom Paris has proposed a follow-up of this PRESTO project in the current ANR open call for project proposals.
- In collaboration with the QTY team, we are also involved in the QSNP European Quantum Flagship (more than 40 partners throughout Europe), providing our expertise on post-quantum cryptography, and exploring its synergy with quantum communications and security.

10.4.2 Research valorization and transfer

Jacques Sakarovitch has developed a software platform alongside Sylvain Lombardy and Victor Marsault for computing with finite automata, called Awali: <http://vaucanson-project.org/Awali/2.3/index.html>

10.4.3 Science popularization

Our research activities are closely related to the work we are doing with our engineer students at Télécom Paris. Through second- and third-year student projects, we familiarize them with research by showing students how they can use their skills in several innovations related to our own research, or to the research projects in which we are working.

We are also currently working with our first-year students to create an educational web game to help the public (children and adults of all ages) to better understand challenges and solutions in cryptography and cybersecurity.

10.4.4 Synthetic self-assessment

We actively contribute to community services, taking on roles such as Program Committee Chair of SCN, General Co-Chair of ACM AsiaCCS, Area Chair of Asiacrypt, and serving as PC members at Crypto, Eurocrypt, Asiacrypt, ACM CCS, etc.

Chapter 11

Self-assessment of DIG team

11.1 Profile, Resources and Organization

11.1.1 Scientific objectives

The DIG team's research interests are focused on the computational aspects of data science, machine learning and artificial intelligence. In general terms, the team's objectives are to make knowledge easy to extract, especially from textual sources, in order to store, process, query, and be understood by machines. More specifically, the DIG team's research activity covers the following topics:

- Database theory,
- Graph mining,
- Machine learning,
- Natural language processing,
- Knowledge bases,
- Machine reasoning,
- Collective intelligence.

Both theoretical and practical aspects are considered. On the theoretical side, for instance, the DIG team works on the theoretical foundations of data management, formal languages, and graph algorithms. The DIG team is also interested in cognitive aspects, such as simplicity theory, seeking to explain the attractiveness of situations or events to human minds, through the notion of algorithmic complexity.

On the practical side, the DIG team develops new approaches to automatically extract structured knowledge from text, new data structures, and languages for storing and querying data, new machine learning algorithms, with a focus on explainable algorithms and online algorithms, new techniques for answering complex questions (e.g. formulated in natural language), along with various applications of these techniques in the fields of industry, health, law and society. The DIG team maintains YAGO, an extensive general knowledge base, and software such as River, Scikit-network, MOA, and Inkscape.

11.1.2 Resources

Team leader: Thomas Bonald (Professor)

Faculty:

- Talel Abdesslem (Professor), also Head of LTCI and Head of research at Télécom Paris

- Mehwish Alam (Associate Professor), since December 2022
- Antoine Amarilli (Associate Professor, HDR)
- Albert Bifet (Professor), also affiliated with the University of Waikato since December 2019
- Thomas Bonald (Professor)
- Jean-Louis Dessalles (Associate Professor), Emeritus since October 2023
- Nils Holzenberger (Associate Professor), since February 2023
- Louis Jachiet (Associate Professor), since September 2019
- Marc Jeanmougin (Research Engineer)
- Mauro Sozio (Professor)
- Fabian Suchanek (Professor)
- Tiphaine Viard (Associate Professor), from September 2020 to August 2022

Post-docs:

- Marie Al-Ghossein, from February 2019 to January 2020
- Maroua Bahri, from June 2020 to June 2021
- Heitor Gomes, until May 2019
- Sven Dziadek (also affiliated with Inria), since September 2023
- Pierre-Henri Paris, since September 2020

11.1.3 Human resources management, safety, environment, ethical protocols, data and scientific heritage protection

The DIG team has signed the **TCS4F manifesto**¹, a pledge for **sustainable research** in theoretical computer science.

Many members of the DIG team have signed the pledge **No Free View? No Review!**² giving priority to **open-access** outlets.

11.1.4 Synthetic self-assessment

Strengths. The DIG team benefits from the high level of synergy between its individual research areas. The cohesion of the team has been considerably strengthened by the recent hiring of Mehwish Alam and Nils Hozenberger. This has created a host of new interactions within the team on the topics of knowledge bases, NLP, as well as symbolic and neuro-symbolic approaches to AI.

Weaknesses. The level of gender parity in the team is unsatisfactory. Furthermore, the move of Albert Bifet to the University of Waikato in New Zealand has weakened the team, especially on the topic of machine learning for data streams.

11.2 Attractiveness

11.2.1 Scientific reputation and contributions

The DIG team has published its research in the best outlets in the field. These publications are extremely visible, with a cumulative number of citations exceeding 50,000 according to Google Scholar.

¹<https://tcs4f.org>

²<https://nofreeviewnoreview.org>

The following awards have been received:

- The Web Conference (2018)
Test of time award
- International Parallel and Distributed Processing Symposium (2019)
Best paper award
- The International Conference on Database Theory (2020)
Best paper award
- International Colloquium on Automata, Languages and Programming (2021)
Best paper award (track B)
- Extended Semantic Web Conference (2021)
Best paper award
- **French Open Science Award** (2022)
- IEEE International Conference on Data Science and Advanced Analytics (2022)
Best Research Paper Award
- ACM Conference on Fairness, Accountability, and Transparency (2023)
Best paper award

The team has also gained considerable visibility through the following **datasets**:

- **YAGO**
<https://yago-knowledge.org>
Large general knowledge base.
- **BLT**
<https://github.com/BlairStanek/BLT/>
Basic Legal Text, a dataset for Legal AI.
- **Netset collection**
<https://netset.telecom-paris.fr>
Collection of network datasets.

and the following **software**:

- **River**
<https://riverml.xyz>
Open-source Python library for online machine learning.
- **Scikit-multiflow**
<https://scikit-multiflow.github.io>
Open-source Python library for online machine learning (merged in River).
- **Scikit-network**
<https://scikit-network.readthedocs.io>
Open-source Python library for graph learning.
- **MOA**
<https://moa.cms.waikato.ac.nz>
Open-source framework for data stream mining (in Java).
- **SAMOA** (until 2021)
<https://incubator.apache.org/projects/samoa.html>
Open-source framework for distributed streaming algorithms (Apache software foundation).
- **AMIE**
<https://github.com/dig-team/amie>
Open-source software to mine Horn rules in knowledge bases (in Java).

- **TorchKGE**
<https://torchkge.readthedocs.io>
Open-source Python library for knowledge graph embedding.
- **Inkscape**
<https://inkscape.org>
Open-source software for vectorial drawing.

Albert Bifet and Fabian Suchanek have given keynotes in major conferences, including:

- ACM International Conference on Distributed and Event-based Systems in New Zealand (2018)
- IEEE International Conference on Big Data Analytics in India (2021)
- Local Chapter of ACM SIGKDD in Singapore (2023)

11.2.2 Staff hosting policy

The DIG team is happy to host visiting researchers. It has notably hosted 2 PhD candidates, Cedric Kulbach from Karlsruhe Institute of Technology (Germany) and Martin Muñoz from Pontificia Universidad Católica de Chile (Chile). Both have participated in the life of the team, including seminars and team-building events, in equal measure to the other team members.

The DIG team has also hosted many researchers for sabbatical stays: Arnaud Soulet (Blois University Institute of Technology), Rodrigo Fernandes de Mello (University of São Paulo, Brazil), Tatiana Nogueira (University Côte d’Azur), Ricardo Rios (Federal University of Bahia, Brazil), Rokia Missaoui (Université du Québec en Outaouais, Canada), Matthieu Jonckheere (University of Buenos Aires, Argentina).

11.2.3 Success in competitive calls for projects

The DIG team has received the following grants from ANR:

- **CQFD** (2018–2024)
<https://anr.fr/Projet-ANR-18-CE23-0003>
ANR project on complex requests for ontologies, beyond the relational model of data.
- **EQUUS** (2019–2025)
<https://anr.fr/Projet-ANR-19-CE48-0019>
ANR project
- **NoRDF** (2020–2024)
<https://nordf.telecom-paris.fr/fr/>
ANR chair on the modeling and extraction of complex information from natural language text.
- **APY** (2021–2024)
<https://apy.hypotheses.org/objectifs>
ANR project on the social-economic model of YouTube.

11.2.4 Synthetic self-assessment

The DIG team is extremely visible and attractive. This is due both to the cohesion of the team and to the quality of its scientific production, in terms of publications, datasets, and software. It also benefits from the skills of its research engineer, Marc Jeanmougin.

11.3 Scientific Production

11.3.1 Qualitative analysis

Topic: Database theory

Contributors: Antoine Amarilli, Louis Jachiet, Fabian Suchanek

Collaborations: Inria, Pontificia Universidad Católica de Chile

PhD theses: François Amat, Julien Romero [238]

The DIG team has worked on the theoretical foundations of data management, in connection with formal language theory. Specifically, we have worked on efficient enumeration, to produce a large collection of query results by listing them in streaming, possibly in some specific order [162]. We have studied enumeration for triangles in large graphs [206], for regular languages [140], for document spanners [130, 210, 132], and for annotated grammars [135]. The team also works on incremental maintenance of data structures, to efficiently maintain query results over changing data, under relabelings [129] or more general updates [131, 136]. The team further investigates the complexity of counting problems, e.g. counting matchings on graphs [139], as well as probabilistic query evaluation for recursive queries [134, 133] in addition to queries relating to uniform probabilistic databases [137, 138].

Other applicative contexts include the interactive evaluation of Boolean provenance [123], the question of data access [183, 125, 127, 240, 239], the design of database views [150], the optimization of recursive queries [198], and query answering with number restrictions [126], order-incomplete data [124], and transitivity constraints [128]. At a more foundational level, the team also studies formal language theory, e.g. topological sorting with regular constraints [141], or sliding window algorithms for formal languages [186].

Topic: Graph mining

Contributors: Talel Abdessalem, Mehwish Alam, Albert Bifet, Thomas Bonald, Jean-Louis Dessalles, Mauro Sozio, Tiphaine Viard

Collaborations: Nokia, Thales, Fraunhofer IWM (Germany), SES department of Télécom Paris.

PhD theses: Gabriel Damay, Simon Delarue, Alexandre Hollocou [193], Nathan de Lara [178], Quentin Lutz [209]

The DIG team possesses solid expertise in graph mining. Several graph algorithms have been designed and analyzed, such as distributed algorithms for k-core decomposition [164] and the computation of betweenness centrality [167, 168, 189], search algorithms for k-cliques [249, 177] and dense subgraphs [249, 235], algorithms for link prediction [166], graph clustering [154, 194, 165] and graph embedding [157, 179]. In response to the need for explanations in decisions, the theory of algorithmic information has been applied to extract relevant subgraphs [180]. The DIG team has also created the open-source Python library scikit-network [155] for machine learning on graphs, including graph neural networks in sparse format [156]. Finally, the DIG team has applied graph mining to a variety of fields, including fatigue prediction in materials [251] through a collaboration with Fraunhofer IWM, event detection [144, 241] and opinion propagation in social networks [163].

Topic: Machine learning

Contributors: Talel Abdessalem, Albert Bifet, Thomas Bonald, Jean-Louis Dessalles, Mauro Sozio, Fabien Suchanek

Collaborations: Safran, University of Waikato (New Zealand)

PhD theses: Subhy Albakour, Maroua Bahri [142], Mariam Barry, Dihia Boulegane [160], Marie Al Ghossein [122], Lanfang Kong, Minh Huong Le Nguyen [204], Jacob Montiel [215], Pierre-Alexandre Murena [217], Edouard Pineau [228], Adrian Putina [230], Nedeljko Radulovic [232]

The DIG team has made several contributions to the area of machine learning, with a focus on explainable AI [233], streaming machine learning [143, 146, 149, 145, 213, 212, 187, 188], and auto Machine Learning [199]. The notion of Kolmogorov complexity has also been applied to optimal transfer machine learning and analogy [219, 220, 217]. The DIG team has co-developed the open-source River [211] and scikit-multiflow [214] Python libraries as well as the MOA Java library for machine learning on data streams. The team has proposed SCALAR, a platform for real-time machine learning competitions [234, 161]. On the application side, the DIG team has developed machine learning algorithms for industry, including predictive maintenance [205, 228], predictive analytics [148], anomaly detection [691] and fraud detection [147], for health with regard to the detection of rare diseases [175] and for society in the prediction of profession from speech [254].

Topic: Natural language processing

Contributors: Mehwish Alam, Thomas Bonald, Jean-Louis Dessalles, Nils Holzenberger, Fabian Suchanek

Collaborations: S²A team, Google, Onepoint

PhD theses: Samed Atouati, Tom Calamai, Lihu Chen [169], Cyril Chhun, Rajaa El Hamdani, Chadi Helwe, Léo Laugier [203], Zacchary Sadeddine

Large language models (LLMs) have both revolutionized the landscape of natural language processing (NLP) and posed new challenges to the scientific community. The DIG team has questioned their robustness [171], their symmetricity [173] (LLMs having difficulty in distinguishing the subject and object of the sentence), and the quality of their representation [174]. On the application side, new approaches have been proposed with regard to the detection and control of toxic comments posted online, through a collaboration with Google [203]. We have also investigated various applications such as patent recommendation [182], biomedical entity linking [170], automated correction of regular expressions [237], and topic modeling in document streams [218]. Finally, the DIG team has provided several datasets for testing LLMs, such as the decoding of ambiguous acronyms [172, 169], the detection of toxic comments [203], the generation of stories [758] and the interpretation of noun phrases [221].

Topic: Knowledge bases

Contributors: Mehwish Alam, Thomas Bonald, Fabian Suchanek

Collaborations: University of Mannheim (Germany), Karlsruhe Institute of Technology (Germany), Max Planck Institute for Informatics (Germany), Ministère des Armées

PhD theses: Armand Boschini [158], Jonathan Lajus [200], Julien Romero [238], Thomas Pellisier Tanon [222], Yiwen Peng

Despite the rise of LLMs, structured data (such as databases or knowledge bases) remain crucial for a wide range of applications [247]. The DIG team works on the creation of knowledge bases (KBs) from natural language text [252, 245, 216, 253], with the YAGO knowledge base [226] as a flagship project. YAGO is freely available, and has won the Test of Time Award at the World Wide Web Conference in 2018 as well as the French Open Science Award in 2022. The team also works on the mining of patterns in KBs, most notably in the AMIE project [200, 201, 246], on the alignment of entities and schemas across KBs [158, 227, 159, 255], and on the automated repair of KBs by means of their edit history [222, 225, 224, 250]. We have also investigated how KBs can be queried efficiently, both in SPARQL [244, 236] and in natural language [223]. Recently, our attention has turned to the incompleteness of KBs and methods to remedy it [248, 243, 202].

On the application side, we have analyzed the various biases of news recommender systems by constructing a knowledge graph from a bilingual news collection on the topic of migration, through a collaboration with the University of Mannheim and Karlsruhe Institute of Technology [197]. We have also produced QUASIMODO, an open-source common-sense knowledge base about object properties, human behavior, and general concepts, through a collaboration with the Max Planck Institute for Informatics³.

Topic: Machine reasoning

Contributors: Jean-Louis Dessalles, Nils Holzenberger, Fabian Suchanek

Collaborations: ACES team, Johns Hopkins University (USA)

PhD theses: Simon Coumes

The DIG team has worked on the reasoning capability of machines, with a focus on the legal field, in collaboration with Johns Hopkins University [151]. We have released a benchmark dataset called SARA for statutory reasoning, a basic task for lawyers and for legal AI, i.e. determine whether a given statute (a law) applies to a given legal case. We have tested GPT-4 on the whole dataset. While GPT-4 did indeed greatly surpass previous models, we found several major weaknesses, prompting follow-up work on LLMs' ability to read and understand legal text [152, 153]. Furthermore, the team has examined the general reasoning capabilities of LLMs [808]. Other contributions of the team relate to semantic analogy [219] and causal inference [184, 185]. The

³<https://quasimodo.mpi-inf.mpg.de>

team has also proposed a computational framework called CompLog, inspired by probabilistic programming systems such as ProbLog, but based on the notion of algorithmic information [242]. Finally, the DIG team has released several tools to the research community: a formal framework for textual entailment [810], a Python library for reasoning based on PyTorch [809], and a MOOC⁴ on algorithmic information and complexity.

Topic: Collective intelligence

Contributors: Jean-Louis Dessalles

Collaborations: ACES team, EDF, Institut Jean Nicod

PhD theses: Etienne Houz  [195], Julien Lie-Panis [207], Samuel Reyd

The DIG team has explored collective intelligence emerging from multiple agents. In his PhD work in cooperation with Institut Jean Nicod, Julien Lie-Panis showed that many cooperative contributions can be simply explained by means of social signaling [207]. In particular, he has proposed a model, called the runaway signal game, that explains how certain useless and yet expensive behaviors may emerge in a population [208]. The team has also addressed the question of explainable AI in decentralized systems such as smart homes [195]. In his PhD in collaboration with the ACES team and EDF, Etienne Houz  showed how to decentralize the necessary expertise and provide useful information to the end user [196].

11.3.2 Scientific integrity, ethics and open science

Antoine Amarilli has launched the pledge **No Free View? No Review!**⁵ giving priority to **open-access** outlets. This pledge has been signed by many members of the DIG team and beyond.

Antoine Amarilli has been managing editor of the new open-access journal TheoretCS⁶ on Theoretical Computer Science.

Many members of the DIG team are involved in free software (including Inkscape, River, scikit-network).

11.3.3 Synthetic self-assessment

Strengths. The DIG team covers a large spectrum of topics in the broad field of databases, machine learning and AI, from the most fundamental aspects (such as the theoretical foundations of data management) to very practical issues (e.g. the maintenance of a large public knowledge base). It is deeply involved in open science and free software.

Weaknesses. The topic on collective intelligence was essentially covered by Jean-Louis Dessalles and might suffer as a result of his new position as Emeritus.

11.4 Contribution of Research Activities to Society

11.4.1 Socioeconomic partnerships and interactions

The DIG team is involved in several industrial partnerships through collaborative projects:

- **ANR chair NoRDF:** EDF, Groupe BPCE, Shlumberger, Sereneo, Converteo, Gendarmerie Nationale, Agence Innovation D fense.
- **ANR project APY:** Wizd o
- **Joint laboratory TALia:** Onepoint

⁴<https://aiai.telecom-paris.fr/>

⁵<https://nofreeviewnoreview.org>

⁶<https://theoretics.episciences.org>

Several PhD theses have been funded by companies through CIFRE contracts (Thales, Nokia, Huawei, Safran, Cisco, Ministère des Armées) or grants (Google).

11.4.2 Research valorization and transfer

Our research on AI for the legal field was prompted by OpenAI's demo of GPT-4⁷ on March 14, 2023: Greg Brockman used an example from the SARA dataset to demonstrate GPT-4's ability to calculate taxes [153].

An approach to predictive maintenance for aircraft engines has been designed with Safran as part of Edouard Pineau's PhD thesis [228]. Specifically, a novel architecture of neural networks has been designed and tested for predicting the aging of an engine from the signal sent by its sensors. A patent has been issued [229].

11.4.3 Science popularization

Jean-Louis Dessalles has been very active in science popularization, especially with regard to AI:

- **Des intelligences TRÈS artificielles** [181]
Jean-Louis Dessalles
Book on AI for non-specialists (2019)
- **De Babel à Google Traduction: vers un nouveau langage universel ?**
<https://www.radiofrance.fr/personnes/jean-louis-dessalles>
Jean-Louis Dessalles
Radio interview at France Culture (2019)
- **Y a-t-il de l'intelligence dans l'intelligence artificielle ?**
Jean-Louis Dessalles
The Conversation (2021)
- **Il existe des limites intrinsèques aux techniques d'IA actuelles**
Jean-Louis Dessalles
Sciences et Avenir (2022)

Fabian Suchanek has also published a paper with Gaël Varoquaux (Inria) on Language Models:

- **On Language Models and Symbolic Representations**
Fabian Suchanek and Gaël Varoquaux
The Conversation (2022)

11.4.4 Synthetic self-assessment

Strengths. The DIG team is involved in many industrial partnerships and has contributed to the popularization of AI and its limits.

Weaknesses. Few results have been transferred to industry in the form of patents, for instance.

⁷<https://www.youtube.com/watch?v=mmOEMfTnQGo>

Chapter 12

Self-assessment of DIVA team

12.1 Profile, Resources and Organization

12.1.1 Scientific objectives

The DIVA team is focused on fundamental and applied research in human-computer interaction and information visualization. It adopts a multidisciplinary approach drawing on computer science, design, and social sciences focused on the computer as a tool through which people interact with the digital world, with its work organized around two major themes: **Novel interactions** to enable and build the user interfaces of tomorrow, and **Homo numericus**, focusing on people's relationship with these technologies. Together, these approaches aim to build future user interfaces by bringing technology and people together.

Novel interactions: This research theme brings together research into new devices (such as skin-based interaction), sensors and form factors, interactive environments (such as virtual/mixed reality and wall-sized interactive spaces), and interaction paradigms (such as malleable, collaborative software for novices and experts). In the period under evaluation, the team has expanded these themes deeper into virtual and mixed reality and into social touch-based interactions.

Homo numericus: This research theme addresses user interfaces and interaction from a user-centered perspective, focusing on how people interact with data, content, and other people as mediated through the human-computer interface. Research in this area includes work on sensemaking in information visualization and data physicalization, on the role of explainability and justifiability in AI-assisted decision-making, empirical work around pointing, memory, and perception as they relate to interactive systems, and on how people learn at scale through computer-mediated learning.

12.1.2 Resources

Generally, the team benefits from a highly developed culture of collaboration, both within the team and its individual projects as well as with other organizations. Within the team, many if not most projects involve co-supervision and collaboration involving multiple team members or across teams. Beyond the team itself, an extensive history of collaboration with other teams (such as the Interact team of CNRS i3), research labs (including LISN, Inria), and fields (e.g. Design, Ergonomics, Sociology, Law) exists. These collaborations result in a diversification and sharing of resources within the team.

Human resources

- Team leader: Eric Lecolinet (founder, until 2021); James Eagan (since April 2021).
- Faculty: James Eagan (Associate Professor), Jan Gugenheimer (Associate Professor, 2019–2022), Eric Lecolinet (Associate Professor; HDR Research Director, Professor, since 2019),

Daniel Pires de Sá Medeiros (Associate Professor, since May 2023), Rémi Sharrock (Associate Professor).

- Associate Members: Samuel Huron (Associate Professor, i3), Tiphaine Viard (MdC, i3).
- Invited Professor: Jan Gugenheimer (TU Darmstadt, since 2022).
- Emeritus Professor: Yves Guiard (Director of Research, CNRS).
- Research Engineer: Mickaël Bouhier (since 2019).
- Visiting Professor: Harpreet Sareen (Assistant Professor, Parsons School of Design, NYC).
- PhD Students: Wen-Jie Tseng, Elise Bonnail, Yan Liu, Astrid Bertrand, Gaëlle Clavelin, Mingming Qiu, Zhuoming Zhang, Samuel Lacroix, Marc Teyssier.
- Post-Docs: Nathalie Bressa, Rafik Belloum, Jessalyn Alva.

Laboratories and platforms

The team participates in running the Télécom Paris FabLab and Design Studio. In addition, the team is in charge of the following immersive labs. It also forms part of the Digiscope and Continuum Equipex consortia in Paris and throughout France:

- PiXLs and IRIS are immersive data environments for interacting with large-scale data. They involve large, wall-sized displays, reconfigurable interactive tabletops/drafting tables, and spatial motion trackers.
- The Mixed-Reality Lab is a virtual and augmented reality immersive laboratory, equipped with various VR and AR headsets and an external spatial motion tracking system.
- Hyve3D is a lightweight immersive cave in collaboration with the i3 lab.
- The Design Studio is a collaborative design space focused on creativity.
- Webstrates (webstrates.net) is a web-based platform based around the fundamental concepts of sharing, malleability, and collaboration. In collaboration with Aarhus University, Télécom Paris, and LRI.

Financial resources

2018-2023 (K€)							
	2018	2019	2020	2021	2022	2023	Total
Public National	27	78	143	182	276	186	892
International							
Partnership & Transfer	36	43	18	18		2	118
Total	63	121	161	200	276	188	1,009

TABLE 12.1: DIVA financial resources.

12.1.3 Human resources management, safety, environment, ethical protocols, data and scientific heritage protection

The DIVA team holds regular team meetings. Before the Covid-19 pandemic, these were scheduled on an ad-hoc basis, approximately once a month. During the pandemic, the team met more informally, holding team meetings by Zoom and creating a Slack space for informal communications. Individual mentorship continued on an ad-hoc basis. As the pandemic wound down, a more regularly scheduled (weekly) team meeting was instituted. This hybrid meeting is held jointly on Zoom and in a videoconferencing space, with additional bi-annual informal gatherings held at the Design Studio in order to maintain cohesion among team members. Guest members are frequently invited to these meetings and social events, including members from TU Darmstadt, and the i3 and LISN research labs.

While the team has been successful in maintaining an approximate gender parity among non-permanent members over the period, permanent staff is heavily male-dominated. The team hopes that future recruitment will help to address this imbalance. Additionally, the team participates in the Télécom Paris ecosystem’s cellule d’écoute program and aims to provide a safe space for all team members.

The DIVA team also participates in the research ethics communities of IP Paris and Université Paris-Saclay. J. Eagan is a founding member and participated in the creation of both the CER-PS and CoER (the research ethics committees of Université Paris-Saclay and IP Paris), and is currently president (since 2023) of the latter. The team submits its research protocols to the appropriate ethics committee and includes discussions of related topics in its team meetings.

12.1.4 Synthetic self-assessment

Strengths: The team has attained a high level of productivity within its respective research areas and has a strong track record of publications, especially at top-tier venues such as ACM CHI and UIST in Human-Computer Interaction, IEEE VIS/TVCG in Visualization, and IEEE VR. It has an outstanding reputation both nationally and internationally, enabling it to attract collaborations, and partnerships, and facilitate recruiting.

Weaknesses and Threats: Its main weaknesses are related to its small size. A new assistant professor was recruited (Jan Gugenheimer 2019-2022) to bring the team size up to four core permanent researchers (not including emeritus, invited, and associate members). However, a competitive offer from TU Darmstadt led to his departure. Daniel Pires de Sá Medeiros was hired in 2023 with a similar research profile, and a new recruitment is underway.

Additionally, while the team has a strong record of gender parity or near-parity for its non-permanent members, its permanent members are predominantly male. The team aims to be inclusive, but this is a difficult long-term problem to address and is limited by long hiring cycles, the strengths of potential candidates, and the small size of the team.

Finally, as a multidisciplinary team, administrative needs are multiplied across departments, research labs, and master’s programs. In addition, several team members serve in leadership roles at Télécom Paris and Institut Polytechnique de Paris, such as on the Research Ethics Committee, the Interaction, Graphics and Design master’s program (founded and chaired by DIVA members), and as members of the Télécom Paris education board. These roles are time-consuming and represent a substantial additional workload for the team, but they are also important missions with regard to the team’s research interests.

Opportunities: At the time of writing of this report, the team is currently recruiting a new assistant professor.

12.2 Attractiveness

12.2.1 Scientific reputation and contributions

DIVA team members are actively involved in their respective scientific communities, at the institutional, local, national, and international levels. These contributions include participation in the human-computer interaction ecosystem at Institut Polytechnique de Paris; organizing the SIGCHI Paris chapter; and participation in organizing and review committees for national and international flagship conferences and journals.

- IP Paris:
 - Master in Computer Science: Interaction, Graphics and Design (E. Lecolinet, J. Eagan, co-chairs)
 - Research Ethics Committee (CoER): J. Eagan, president
- Organizing committees

- ACM UIST: J. Eagan, Visions Chair 2021
- ACM Pervasive Displays (PERDIS): J. Gugenheimer, Program Co-Chair 2020
- ACM CHI: J. Gugenheimer, Workshop organizer, 2019-2020; S. Huron, Workshop organizer, 2023
- IEEE VIS: S. Huron, Workshop organizer, 2018, 2020
- Program committees
 - J. Gugenheimer (ACM CHI, 2019-2023; ACM ISS, 2019; ACM MUM, 2019; Mensch und Computer, 2019)
 - S. Huron (ACM CHI, 2023; IEEE VIS, 2018, 2020-2022)
 - J. Eagan (ACM CHI 2019-2020; IEEE VIS, 2020-2023)
- National and local:
 - Association Francophone de l'Interaction Humain-Machine (AFIHM): E. Lecolinet, president 2017-2021; J. Eagan, conseil d'administration, 2018-2019
 - ACM SIGCHI Paris Chapter (S. Huron, president; J. Eagan, former president, vice-president)

12.2.2 Staff hosting policy

The DIVA team competitively recruits international and national candidates for PhDs, post-docs, Visiting researchers, and interns. PhD and post-docs have been recruited from such schools as National Chiao Tung University, Taiwan; Aarhus University, Denmark; HEC, France; and Université Paris-Saclay, France. The team also hosted H. Sareen, a visiting researcher from the Parsons School in New York.

New recruits to the team are assigned a mentor to help facilitate their integration. Team members are grouped into shared labs or offices to encourage collaboration and the informal free exchange of ideas. Additionally, the team holds a weekly team meeting for more formal exchanges, and less regular team-building activities several times a year (such as "secret santa" gift exchanges, crêpes/galette des rois, or alumni dinners at conferences) to foster informal exchanges.

Team members are encouraged to freely collaborate and exchange ideas through this mix of formal and informal exchanges, and different projects and publications can spontaneously arise through this mix of ideas, as shown through the many collaboratively authored publications involving multiple team members. Furthermore, the team makes its publications available wherever possible via open science archives such as HAL, and solicits ethical reviews for its studies through the Research Ethics Committees of Université Paris-Saclay and Institut Polytechnique de Paris. J. Eagan participated in the creation of both of these committees and serves as president of the latter.

12.2.3 Success in competitive calls for projects

The DIVA team participates in a variety of national and local projects, funded by the ANR, the BPI, and individual bilateral contracts, including CIFRE. A selection of projects won by the team over the period is given in the following table.

TYPE	ACRONYM	START	END	BUDGET
ANR	EQUIPEX - Continuum	01/06/2021	31/05/2029	261,960
ANR	HARMFULVR (JCJC)	01/10/2021	31/03/2022	12,797
ANR	SecondSkin	01/10/2021	30/09/2025	240,572
ANR	INTERPLAY	01/10/2021	30/09/2025	164,017
Labex DigiCosme	Harpreet SAREEN Sabbatical	01/04/2021	31/12/2022	13,520
CIFRE	PhD of Mingming QIU	01/02/2019	28/02/2023	54,000
Public (non ANR)	TOUCAN (trophées Innov. Numérique)	17/10/2018	16/10/2021	46,200

TYPE	ACRONYM	START	END	BUDGET
Public (non ANR)	PIA - TIP #GENIUS project	01/08/2019	31/12/2022	62,776
Public (non ANR)	PIA-PSPC-Régions WIZARD project	01/06/2020	30/11/2022	147,699
Public (non ANR)	CALAO (trophées Innov. Numérique)	23/09/2020	29/12/2023	140,000

12.2.4 Equipment quality and technological skills

The DIVA team maintains several research laboratories: the PIXLs and IRIS wall-sized display labs (funded through the EQUIPEX Digiscope and Continuum grants), a mixed-reality lab (Continuum), and the FabLab and Design Studios at Télécom Paris. A permanent research engineer (M. Bouhier) maintains these labs and provides personal support for projects that use them. Together, this work has been instrumental in supporting the majority of the team's various research projects (see publications).

12.2.5 Synthetic self-assessment

Strengths: The team is generally able to successfully "punch above its weight", attracting exceptional candidates, both nationally and internationally. Its collaborations are enabled through participation in national partnerships (for example, ANR projects with multiple national partners), industry projects (e.g. Île-de-France PSPC Wizard, CIFRE EDF), and via internal funding sources (IMT, Carnot) that have led to the creation of projects such as ANR SocialTouch and SecondSkin.

Weaknesses and Threats: The team faces two main threats in this respect: its small size makes it more susceptible to the cyclical nature of funding and recruitment. Furthermore, it has a small base of industrial partnerships which are necessary to provide the funding for missions in addition to facing constraints in terms of resources and equipment. The limited funding for personnel and the pre-HDR skew of the team are the primary obstacles with regard to manpower and scientific production.

Opportunities: The additional visibility gained through the IP Paris project provides an increased opportunity to capitalize on the team's attractiveness. With adequate resources, the team should further enhance its ability to develop international exchanges and partnerships.

12.3 Scientific Production

12.3.1 Qualitative analysis

While the team produces software artifacts (such as the Webstrates platform), has work on display at the Museum of Immigration in Paris (M. Bouhier in collaboration with D. Dimenescu of i3), and has produced several patents (2 in the review period), the bulk of the team's scientific production is in the form of academic publications. In Human-Computer Interaction, the flagship publishing venue is the ACM CHI conference, which is generally regarded as having top-tier journal-level impact and rigor. The team also publishes at the top ACM UIST and IEEE VIS and VR conferences (and their accompanying TVCG journal tracks). These flagship venues constitute the core of the team's publishing activities, although it also target more specialized conferences within the HCI, Visualization, and VR communities. Its publication history at these flagship venues is competitive with much larger institutions in the field: nationally, in Europe, and internationally. The team benefits from close collaborations with teams in France, in Europe and the UK, and North America.

Its work is structured around two main themes:

Novel interactions: Work in this area has focused on two main areas of application: new types of devices and interactions for supporting social uses of touch-based interfaces, as exemplified

by MobiLimb [257], and interaction in Mixed Reality, such as dark patterns and memory manipulations [256]. This work led to two ANR projects (SocialTouch and SecondSkin), including a national consortium around these topics for the latter. The first of these pushes the team's research into a new area that leverages its expertise in both hardware device-building and human-centered interaction techniques. The second of these expands into human-oriented uses of virtual and augmented reality.

Homo numericus: Continuing the team's line of research into how people interact with their digital worlds, work in this area has explored how data workers interact with and make sense of data and has further expanded into physical representations of data. The work on Webstrates continues to focus on empowering computationally literate expert users to appropriate and adapt digital tools to their idiosyncratic needs. The team has been instrumental in building research communities around these topics through international and national collaborations, such as with the University of Calgary and Aarhus University.

12.3.2 Potential and dissemination strategy

Internal team-building and collaboration draw on two main strategies: a structured, weekly meeting gathering the whole team in which all team members start with a lightning presentation of their work and concerns. This helps all members, regardless of seniority and stage of advancement of their projects, to follow and exchange ideas on each others' work. The second internal strategy focuses on informal exchanges, through impromptu coffee breaks, informal social activities, and lunches. These activities provide for improvised and low-key exchanges and explorations to develop new topics of interest. Externally, the team encourages collaboration, as can be attested by the number of cross-institutional and international collaborations.

12.3.3 Scientific integrity, ethics and open science

As a human-centric team conducting research into human-computer interaction, people are at the center of the team's work: both as target users for the systems it builds and as participants in research experiments. The team routinely submits its research protocols to the relevant ethics review boards, such as the CER-Paris Saclay and the newly-created Comité d'Éthique pour la Recherche (CoER) of IP Paris, both of which J. Eagan is a founding member.

Moreover, one of the team's research angles focuses on understanding risks and mitigations of harm arising from virtual reality, including memory manipulations and self-harm in VR.

Additionally, the team generally takes a positive approach to open science, eschewing patents, and favoring the publishing of its work in open archives such as HAL. The team is increasingly exploring ways to place intermediate research artifacts, including code and experimental data, into open research archives such as OSF.

12.3.4 Synthetic self-assessment

Strengths: The team has a strong track record of top-tier publications in national and international venues. It further benefits from a strong network of national and international academic collaborations, both on individual research projects and in the creation of broader consortia, such as ANR SocialTouch and ANR SecondSkin, and participation in the Equipex Digiscope and Continuum.

Weaknesses and Threats: The team's small size makes it particularly susceptible to the cycles of funding and recruitment, and further limits the teams' ability to share the administrative burden across a broader base. This latter point is also exacerbated by the number of junior members (which should lessen over time).

Opportunities: The team benefits from excellent institutional support and technological resources, such as the Digiscope, Continuum, and Mixed-Reality platforms, the Design Studio and FabLab, and research engineer support. These resources offer an exciting potential for growth with sufficient personnel, such as through PhD students and post-docs.

12.4 Contribution of Research Activities to Society

12.4.1 Socioeconomic partnerships and interactions

The team has participated in industry-related projects, such as a CIFRE with EDF and the PSPC Wizard project. Additionally, the team's work with D. Dimensescu of the i3 lab is currently on exhibit at the Musée de l'Immigration in Paris.

12.4.2 Research valorization and transfer

While the team favors open dissemination of its work, including through open source software (e.g. Webstrates), it has nonetheless been involved in two patents through its work in the SocialTouch project.

12.4.3 Science popularization

The team has collaborated with Dana Dimenescu of the i3 research lab, including an exhibition at the Musée de l'Immigration that blends interaction techniques developed in the laboratory to provide visitors with an immersive experience around the theme of refugees and host families. Additionally, the team's research lines offer encouraging prospects for societal impact. In particular, the team's work around potential dangers of Mixed Reality, harm, and memory explores societal impact for future uses of these technologies. Work in Skin-On interfaces and In-Flat that has been picked up by the technology press as well as the BBC contributes to the popularization of the techniques being developed as part of the team's work.

Finally, the team has had significant involvement in the Association Francophone de l'Interaction Humain-Machine (AFIHM), which has a structuring and animating role in HCI in France and the French-speaking world.

12.4.4 Synthetic self-assessment

Strengths: The team's work has wider societal and technological applicability, from installations at the Musée de l'Immigration to more exploratory initiatives garnering mainstream and tech press attention (e.g. Skin-On, In-Flat). Moreover, the team's work into potential harms and mitigations in Virtual/Augmented/Mixed Reality contexts helps guide future research and its applications in this burgeoning field.

The team further aims to disseminate its work through open publications, open-source software artifacts, and do-it-yourself (DIY) guides to facilitate the uptake of its research outputs.

Finally, the team's participation in the IP Paris and Paris-Saclay research ethics boards demonstrates a leadership role in guiding the evolution of broader non-biomedical research at these institutions. It is also actively involved in the Association Francophone pour l'Interaction Humain-Machine, a learned society with a structuring and animating role for HCI research in France and the francophone world, but also beyond.

Weaknesses and Opportunities: While the team has had several fruitful industrial collaborations (through CIFRE, the BPI, etc.), the team's research work primarily focuses on more academic projects and collaborations. This is an area the team could develop more, with parsimony.

Threats: The team's relatively small size limits its capacity to solicit and respond to partnership opportunities. This is compounded by a shortfall of HDRs in the team (NB: two are in the process of being written; S. Huron and J. Eagan) and by the evolving demographics of the team, with one emeritus member (Y. Guiard) and one senior member (E. Lecolinet) due to retire within the next evaluation period.

Chapter 13

Self-assessment of QURIOSITY team

13.1 Profile, Resources and Organization

13.1.1 Scientific objectives

The objective of the QURIOSITY team is to extend the application horizons of quantum information science by addressing novel questions positioned at the intersection between theoretical research in quantum information and the engineering of quantum devices, with a focus on theoretical questions and a multidisciplinary approach combining mathematics, computer science, and physics. An overarching goal of the team is to push forward our ability to harness and exploit high-dimensional complex quantum systems for quantum information processing and quantum communications purposes.

The team is fully integrated within the LTCI at Télécom Paris, with a significant collaboration with GTO over the period (two shared PhD students), and forms part of the Computer Science Department IDIA at Institut Polytechnique de Paris. QURIOSITY also benefits from interactions with some existing Inria quantum teams (notably QINFO, GRACE and COSMIQ), as well as from an active network of international collaborations (University of Edinburgh, University of Geneva, IQOQI Vienna, University of Cambridge, Complutense University of Madrid, University of York, IQC Waterloo), and also from strong synergies with entities within IP Paris and Saclay working on quantum information theory, quantum computer science and quantum photonics (Inria teams QuACS and PHIQUS, CEA-IPhT, C2N, IOGS), in addition to teaching (QMI project to develop a new M2 in Quantum, Mathematics, Informatics) and industrial collaborations (as we shall describe in [13.4.1](#)).

13.1.2 Resources

The QURIOSITY team has significantly evolved during the period under review. The previous team, known as IQA, was composed of three permanent members at the beginning of the period, in 2018. It was then reduced to a single permanent member (Romain Alléaume) in fall 2020, after the departure of Filippo Miatto (to Xanadu, Canada) and the move of Isabelle Zaquine to the GTO team. Capitalizing on IQA's scientific reputation in quantum cryptography and quantum communications, and pursuing the motivation to evolve thematically towards quantum computer science, the team has been rebuilt, with the combined support of Télécom Paris, Inria and IP Paris. QURIOSITY has benefited from 4 strategic hires (Peter Brown in 2021, Cambyse Rouzé in 2022, Augustin Vanrietvelde in 2023, and Mirjam Weilenmann, who was recruited by Inria in 2023 and will arrive in February 2025). The QURIOSITY team officially became a joint Inria-IPP team on January 1st 2023. Thanks to the recent hires, the team boasts broad-ranging expertise in quantum information theory and quantum information processing, combining in particular expertise in mathematics, computer science and physics. It also benefits from long-term expertise in quantum communications and quantum cryptography, both at theory and engineering levels.

- *Human resources*

Faculty:

Romain Alléaume (Professor, Team leader since November 2020), Peter Brown (Associate Professor), Cambyse Rouzé (Inria Starting Faculty), Augustin Vanrietvelde (Associate Professor), Filippo Miatto (Associate Professor, until November 2020), Isabelle Zaquine (Professor and IQA team leader until November 2020), Filippo Miatto (Invited Associate Professor, since November 2020).

PhD Students

Niraj Kumar (March 2015-December 2018), Martin Cordier (October 2015-May 2019), Mathieu Bozzio (October 2016-December 2019), Nilesh Vyas (April 2018-December 2021), Yuan Yao (October 2019-February 2023), Raphael Aymeric (October 2019-October 2022), Antoine Henry (October 2020-December 2023), Francesco Mazzoncini (September 2020-defense planned in June 2024), Guillaume Ricard (September 2021-present), Pierre-Enguerrand Verdier (September 2022-present), Tristan Nemoz (November 2022-present), Jan Kochanowski (November 2023-present), Paul Gondolf (October 2022-present) registered at University of Tübingen, Sebastian Stengele, (March 2023-present) registered at TUM, Thomas Pousset (November 2023-present).

Master Students (incomplete list)

Francesco Mazzoncini (January 2020-August 2020), Richard Wolf (September 2020-July 2021), Evdokia Gneusheva (January 2023-March 2023), Ali Almasi (September 2023-present).

Post-Docs Ravi Ragnathan (January 2018-December 2019), Thomas Van Himbeek (October 2022-present).

- *Financial resources*

Over the period the financial resources secured by the IQA (later QURIOSITY) team, consisting of PhD grants, and regional funding from DIM SIRTEQ, while mainly derived from European projects associated in particular with the Quantum Technology Flagship.

The team's total financial resources are approaching €1.5M over the period.

This level of funding is relatively important considering the size of the team over the period. Moreover, sizable contracts were secured at the end of the period (European project QSNP, and PEPR QCommTestbed see 13.2.3). This has helped to attract talent and has also encouraged a positive dynamic enabling the QURIOSITY team to launch on an ambitious footing.

13.1.3 Human resources management, safety, environment, ethical protocols, data and scientific heritage protection

As detailed in 13.1.2, the team's composition and size have significantly evolved over the period, with a notable increase in the number of permanent and non-permanent members since November 2023. This evolution has also enabled a structuring of the team's activity, including weekly team meetings, weekly team seminars with invited external speakers, as well as presentations by team members and in particular PhD students. On a bi-monthly basis, the team participates in (and organizes about twice a year) the Saclay Quantum Information gathering, composed of a tutorial and research talks. The team also organizes a selection of social events.

QURIOSITY promotes inclusion and diversity in terms of its permanent and non-permanent recruitment. Gender balance at the end of 2023 is unsatisfactory (the 4 permanent members are male), but is set to improve in February 2025 when Mirjam Weillenman joins QURIOSITY. The team management philosophy also consists of sharing opportunities to gain external visibility with early-stage permanent researchers, positioned as principal investigators in their core topics. Reducing the environmental footprint of its activity is an important concern for the team, which favors participation in dissemination events (conferences, workshops) in Europe, with travel preferentially by train.

13.1.4 Synthetic self-assessment

Strengths: The team has maintained a record of high-quality publications throughout the period, with exceptional results at QIP in the final year (see portfolio). It has been able to capitalize on its historical strength and reputation in quantum communications (notably within the European research ecosystem), to expand toward quantum mathematics and computer science. QURIOSITY members have been granted key leadership roles in the Quantum Technology Flagship and the PEPR Quantique. With the support of Inria and Télécom Paris, the team has successfully recruited 4 extremely talented young researchers, over three consecutive years from 2021 to 2023. It is now a joint team with Inria, which serves to increase its visibility and opportunities for partnerships.

Weaknesses: The number of HDR permanent members in the team is insufficient to cover the direction of future PhD students that will join the team. This mismatch is currently being addressed with derogations. It will also lead to the preparation and defense of several HDRs over the next period.

Opportunities: The Saclay ecosystem is historically a leading expert in quantum technologies, in particular in physics. On the other hand, quantum mathematics and quantum computer science were almost not present at Saclay at the beginning of the period. Seizing the opportunities offered by the Quantum Technology Flagship and the Plan National Quantique, IQA and its successor QURIOSITY have actively contributed to the development of this field, at IP Paris level. Moreover, QURIOSITY intends to federate forces in quantum information theory and quantum computer science from the Saclay ecosystem to launch an M2 on Quantum, Mathematics and Informatics (QMI).

Threats: The team has historically been oriented toward a high level of activity in experimental quantum communications. With the departure of Eleni Diamanti (in 2016) and Isabelle Zaquine (2020), the remaining experimental activities led by Romain Alléaume are now led in collaborations (with the GTO team, ENS Paris and C2N), which has led to positive outcomes, but may also reduce the sustainability of these activities within the team.

13.2 Attractiveness

13.2.1 Scientific reputation and contributions

The QURIOSITY team actively contributes to key programs in quantum science and technology, such as the Quantum Technology Flagship (projects CIVIQ, QSNP and FranceQCI), and the Stratégie Nationale Quantique (PEPR QCommTestbed). Team members publish papers in high-profile journals both in physics and mathematics such as Physical Review, Quantum, Nature, and IEEE Transactions on Information Theory, as well as at top conferences in quantum computer science and quantum engineering such as QIP, QCrypt, TQC, and OFC. Team members are also regularly invited as speakers to national and international scientific events, and invited to be part of the TPC of flagship conferences such as QCrypt and QIP. A non-exhaustive list of contributions include:

- **Participation in conference organization and technical program committee (TPC)**
Organizing committee of ICQCOM International Conference on Quantum Communication Oct. 2021, TPC member of QCall Final Symposium in May 2021, TPC member of QCrypt in August 2021, TPC of TPC IEEE ICC’23, Organizing Committee of the Quantum Hardware Security workshop Edinburgh in October 2023, TPC member of QIP and QIP 2024.

- **Participation in research steering and evaluation committees**
 - * Expertise for the European Commission (DG CNECT) on Quantum Communications and Quantum Networks, for the preparation of the QT Flagship and EuroQCI (2018 to 2019).
 - * Auditioned by the Mission Parlementaire Forteza on Stratégie Quantique Nationale (May 2019) and contributor to the definition of the Plan Quantique (2019-2020).
 - * Member of the executive committee of the Quantum-Saclay center, one of the three main national quantum hubs, 2020-present.
 - * Member of the Alliance Quantum Evaluation Committee, at NSERC, in charge of scientific evaluation of Canada Quantum Grants Applications (4 sessions per year), 2022-present.
 - * Participation in evaluation and recruitment committees at Télécom Paris (OpenQKD Open calls (2021), Quantum-Saclay center (2021-23), Ecole Polytechnique (2023), Sorbonne Université quantum center (2023).
- **Invited talks (selection)**
 - * IDQuantique Winter School, January 2018.
 - * Cisco - Polytechnique Annual Symposium - April 9-10 2018.
 - * Workshop "The Quantum Internet, Charting the Critical Path", June 21-23 2018, University of Toronto.
 - * Workshop "Quantum Communications for Secure Optical Networks", ECOC 2018, Rome, September 2018.
 - * CRISIS Workshop on PQC, November 2020.
 - * RISQ workshop on Post-Quantum Cryptography, March 2020.
 - * BSI Workshop on Implementation Attacks on QKD systems, June 2021.
 - * GAP-Optique Seminar, University of Geneva, February 2022.
 - * Conseil Scientifique de l'INS2I, CNRS, October 2022.
 - * Security of QKD workshop (5th edition), IQC Waterloo, Canada, September 2023.
 - * Workshop on Gaussian and non-Gaussian Quantum Correlations, Copenhagen Denmark, November 2023.
 - * Quantum Secure Network Partnership representation, ICFO, Barcelona, May 25 2023.
 - * Workshop on Quantum Ecology, Leyzin Switzerland, July 2023.

13.2.2 Staff hosting policy

Over the period, the team first experienced one departure to the start-up Xanadu in Canada, then another to the GTO team. It thus reconfigured its positioning, towards quantum information theory and quantum computing and hired 4 new permanent team members, 2 with Télécom Paris positions, and 2 with Inria positions. In the Télécom Paris recruitment procedure, there was a large number of very good candidates, and (taking into consideration concurrent applications to QURIOSITY via Inria) candidates ranked 1st and accepted the position. Concerning the Inria competitive recruitment campaigns in 2022 and 2023, the candidates who joined our team were both ranked in first position (at admissibility and admission) out of the ≈ 50 candidates at Inria Saclay level. All four candidates are exogenous to the team, and two are non-French. The creation of a new Inria team has been supported by IP Paris and ANR ExcellenceS, forming part of its scientific development strategy. This has enabled the proposal of 3 attractive starting packages (€250K) to the last 3 recruits. In addition, funding from already secured contracts, and the possibility of contributing to European projects as PIs, is shared with researchers recently recruited to the team.

13.2.3 Success in competitive calls for projects

Funded projects A key characteristic of the QURIOSITY team, the successor to IQA, is its active participation in the European research ecosystem. Despite the departure of 3 close IQA

colleagues affiliated to CNRS, in 2016 (to LIP6). This active participation in the European research ecosystem has somehow been continued and even amplified over the last period, with notable success in competitive calls, further boosted by the Quantum Technology Flagship and the Plan National Quantique. We list below the main funded projects over the period:

- PEPR project QuantumCommTestbed, dedicated to fundamental research into novel quantum communication systems and their field deployment, (2023-2027).
- Quantum Encryption and Future Quantum Networks (QSNP), Federated Partnership Agreement of the Quantum Technology Flagship, Quantum Communication pillar, (2023-2026).
- France QCI, Digital Europe Program related to Quantum Communication Infrastructure National deployment, (2023-2025).
- ParisRegionQCI, Project supported by Paris Region, (2021-2024).
- ParisQCI: SIRTEQ Synergy Grant, (2021-2023).
- QSAFE and EuroQCI4EU: Two Studies for the European Commission on EuroQCI, (2021-2022).
- OPENQKD (Open European Quantum Key Distribution Testbed). Research and Innovation Action, Quantum Technology Flagship, (2019-2023).
- CiViQ (Continuous Variable Quantum Communications). Research and Innovation Action, Quantum Technology Flagship / Q communications pillar, (project No 820466), (2018-2022).
- QCALL, International Training Network, Marie Curie H2020 program, (2017-2021).

13.2.4 Equipment quality and technological skills

QURIOSITY conducts activity on quantum communication engineering, mostly in collaboration with other teams: with ENS Paris and the team led by Sylvain Gigan on quantum programmable spatial multimode optics (paper in preparation); with C2N on frequency multimode processor [590]; with the GTO team, as part of CIVIQ and QSNP and leveraging their state of the art 40 Gb/s optical communication platform, on quantum coherent communications [580, 579, 578]. In collaboration with Orange, and GTO, QURIOSITY has also steered the deployment of the Paris-RegionQCI network in Saclay, in particular a "quantum backbone" fiber link connecting Télécom Paris (Palaiseau) to Orange Innovation (Chatillon) and Sorbonne Université (Paris, Jussieu), as well as the establishment of local connections with IOGS, TRT and C2N. This quantum network constitutes a strategic asset for future projects (notably FranceQCI).

13.2.5 Synthetic self-assessment

Strengths: The period has been exceptional for the team, in terms of recruitment, the association with Inria, and the creation of a new team (EPC¹), as well as the involvement in key strategic projects (QT Flagship, PEPR Quantique). All these factors as well as the exceptional quality of candidates (for the opened permanent positions) and of the student applications (at master's and PhD level) that the team receives indicate a very high level of attractiveness.

Threat Strategic investment in quantum technologies may not continue at the same pace in the coming years. The team has however secured a certain amount of long-term funding (PEPR and ExcellenceS both until 2027) that enables us to mitigate this risk.

¹Equipe project commune

13.3 Scientific Production

13.3.1 Qualitative analysis

The team publishes in the highest quality journals on theoretical aspects of quantum information science, with publication in top-tier outlets such as *Quantum* (2), *npj Quantum Information* (2), *Communications in Mathematical Physics* (1), *PRX Quantum* (1), and *IEEE Transactions in Information Theory* (1). It also publishes in top-tier outlets on experimental quantum information science and quantum engineering, such as *Physical Review Letters* (1), *Physical Review A* (4), *IEEE Photonic Journal*, *Scientific Reports* (2), *Journal of Optics*, and *Optics Express*. In addition, the work of the team has been regularly presented at the top international conferences in their respective domain, notably QIP (5) (see portfolio), QCrypt (3) and OFC (2).

We can categorize contributions into 3 main areas. The first, on quantum sources of light and non-linear optics, was coordinated by Isabelle Zaquine, who moved to the GTO team during the period. The remaining 2 areas, respectively on quantum communications and photonic quantum information processing and (theoretical) quantum cryptography and quantum information theory, correspond to the QURIOSITY research program, that was initiated in 2023.

Quantum sources of light and non-linear optics

Non-linear optics is an essential component of the quantum communication and photonic quantum computing toolbox, in particular for the creation of entangled pairs of photons and squeezed light. In the context of research outlined in the PhD thesis by Martin Cordier [585], the team has made key progress in demonstrating how, by exploiting four-wave mixing, hollow-core fibers could be used to create and spectrally engineer a versatile source of entangled photon-pairs at telecom wavelength [587, 589, 586, 586, 572, 598]. These results are promising for quantum communications, since hollow-core fibers have a very low Raman scattering cross-section and could therefore be used to jointly deploy classical and quantum communications, without noise penalty affecting the latter.

Quantum communications and photonic quantum information processing

The team has a strong reputation and expertise concerning quantum key distribution (QKD), including the creation of SeQureNet, the first start-up to commercialize continuous-variable QKD (CV-QKD) in 2013, with participation in leading European projects on these topics (SECOQC, Q-CERT, QCALL). During the concerned period, the team has initiated a fruitful collaboration with the GTO team (Yves Jaouën) on quantum coherent communication and digital signal processing, as part of the CIVIQ and then QSNP research projects. In particular, we have demonstrated for the first time the possibility of using a single transmitter and a single channel to jointly perform classical communication and QKD, paving the way for highly integrated and cost-effective quantum communications. [579, 580]. In collaboration with former CNRS colleagues (now at LIP6) the team worked on quantum money and quantum coin flipping, providing some of its first experimental demonstrations [583, 581, 582]. Particular attention has also been paid to the question (that is now becoming crucial in the context of EuroQCI) of implementation security, with the ETSI QKD Industry standardization group [573], but also by identifying a novel attack vector against CV-QKD based on detector saturation [599](see portfolio), and then showing how the attack ratings methodology inherited from the Common Criteria, can be applied to QKD [594]. More broadly, Romain Alléaume published his HDR on Quantum cryptography and its application frontiers [576] and the team made contributions to quantum networking standards [575], structure of one-way quantum repeaters [596] while also clarifying the conditions for long-range QKD in partnership with key international leaders [592]. Finally, in collaboration with C2N, the team made its first contributions to photonic quantum computing, with the theoretical study of qubit gate synthesis using a time-frequency quantum processor [590, 600].

Quantum cryptography and quantum information theory

QURIOSITY has increased its activity in theoretical quantum cryptography during the period,

at the frontier between quantum (and classical) information theory and theoretical computer science. This has consisted in exploring the tight analytic trade-off between device-independence randomness and nonlocality [603], as well as the development of new ways to certify properties of quantum systems using Bell tests [604, 605]. A new line of research has consisted of exploring how computational assumptions could boost the performance of quantum cryptographic schemes while maintaining an edge in terms of security. Introducing a new security model, we have presented a new framework for hybrid quantum cryptography [577, 574] and recently proved that its security could be reduced to classical vs quantum computational complexity gap [595]. This opens up interesting perspectives (see portfolio) that are explored within the European project QSNP, as part of which our team coordinates the work on quantum and classical (post-quantum) cryptography convergence, and has moreover developed partnerships, within IP Paris, with the C2 team and the GRACE team on this topic.

Thanks to newly recruited team members, QURIOSITY has strongly developed its research on quantum information theory, and already positioned it at the international level, with 5 accepted talks for instance at QIP 2024 (see portfolio). One topic is related to the study of quantum correlations and quantum entropies, notably using convex optimization techniques [601]. As outlined in portfolio contribution 4, the team has recently developed a novel framework for the security proof of quantum key distribution (QKD), that is general and tight in terms of finite-size dependence. An information-theoretic lens was used to approach quantum differential privacy [591], but also bounds form on statistical learning from quantum data [584], in addition to the dynamic of the Zeno effect in open quantum systems in infinite dimension [597]. Leveraging the classical theory of optimal transport, quantum optimal transport has been used to shed new light on certain fundamental limits for quantum computing in the presence of noise, namely what is achievable with variational quantum algorithms [588], but also establishing a new analytic upper bound on the fault-tolerance threshold for concatenated GKP-stabilizer codes with local update recovery [593].

13.3.2 Potential and dissemination strategy

The IQA and later the QURIOSITY team have gone through a major transition during the period under review, with a very high turnover rate, as partially reflected by Table 13.3.2 below. We can see that the level of publications has remained essentially proportionate to the number of permanent members. 2021 in particular was a notably slow year, with a low publication level, which can be explained by the fact that the team was reduced to a single permanent member who was writing and also defended his HDR around that time. We can also note that there was a clear increase in the publication dynamic in 2022, and even more so in 2023, which moreover does not take into account the remarkable results obtained in 2023, with 1 accepted talk at QCrypt2023 and at QIP2024.

Publications 2018-2023 (source: HAL)						
Year	Total	Journal	Proceedings	Chapters/Reports	HDR	Number of permanent members
2018	9	5	3	1	-	2
2019	10	2	5	3	-	3
2020	4	2	1	1	-	2
2021	3	1	1	1	1	1
2022	8	6	2	-	-	2
2023	11	5	-	6	-	3

Young researchers, who are newly recruited to the team, are encouraged to act as principal investigators (PIs), i.e. lead one or several research initiatives. This is reflected in the article signature policy (last author position), but also supported by starting packages and /or by sharing research funding, as well as PI responsibilities.

13.3.3 Scientific integrity, ethics and open science

QURIOSITY values scientific integrity and seeks to encourage it by promoting a range of organizational procedures such as regular and open information sharing (team meetings, internal discussion forums), the systematic organization of practice talks ahead of conferences, and proofreading. We also favor open-access journals and avoid predatory ones. Concerned about their carbon footprint, QURIOSITY team members have reduced the number of plane trips, substituting them with train travel but also with less frequent long-distance trips.

13.3.4 Synthetic self-assessment

Strengths: In terms of scientific production, the strengths of the team lie in its capacity to publish and present its research in the most selective international outlets, and also to prioritize the impact and novelty of research actions and questions - which in general take more time - over quantity. The acceptance of 5 submissions produced by our team members (including lengthy technical papers) and our ambitious scientific objectives for QIP2024 (see portfolio) illustrates this trait. Another positive point has been the ability of the team to undergo an important thematic evolution, with a greater focus on theoretical computer science and mathematics while maintaining synergies and continuity concerning the activity on quantum communications.

Weaknesses: The specific efforts to develop QURIOSITY in collaboration with Télécom Paris and IP Paris, but also more generally the institutional instability and complexity related to the development of IP Paris, incur a significant workload in terms of team administration and management, with a negative impact on team scientific production (particularly important in the proportion of the total production, when the team was reduced to 1 or 2 permanent members).

Opportunities: The quantum science and technology (QST) environment at Saclay is extremely dynamic with historic strengths in quantum physics and now emerging forces in quantum information and quantum CS, while drawing on a pool of top-level "non-quantum" researchers in physics and mathematics with relevant expertise to further advance the frontier of knowledge and technology in QST.

13.4 Contribution of Research Activities to Society

13.4.1 Socio-economic partnerships and interactions

QURIOSITY can draw on an extensive network of industrial collaborations on quantum communications developed by IQA and also its (former) spin-off SeQureNet. Furthermore, the team is gradually expanding these collaborations to quantum computing. We list the main ones below, in addition to the related topics and (if relevant), the associated collaborative project.

- Orange Labs (Chatillon): quantum cryptography, quantum networking. CIVIQ, OpenQKD, ParisRegionQCI with a joint CIFRE PhD.
- Thales (TRT Palaiseau, SIX): quantum sensing, quantum communications, post-quantum cryptography. OpenQKD, QSAFE, FranceQCI.
- Airbus (Toulouse): quantum cryptography, satellite communications. FranceQCI.
- Quandela (Palaiseau, SME): quantum communications, photonic quantum computing. Paris-RegionPhD grant, ParisRegionQCI.
- VeriQloud (SME, Montrouge): quantum internet, quantum cryptography. ParisRegionQCI. ParisRegionQCI, FranceQCI.
- CryptoNext (SME, Paris): post-quantum cryptography, QSAFE, ParisRegionQCI. ParisRegionQCI, FranceQCI, QSAFE, FPA QSNP.

- Nokia Bell Labs (Nozay): quantum coherent communications systems CIVIQ, OpenQKD, Paris-RegionQCI.

13.4.2 Research valorization and transfer

QURIOSITY currently holds 5 granted patents: 3 on hybrid quantum computational cryptography, i.e. related to [577, 574, 595] and 2 on quantum coherent communications, related to [580, 579, 578]. We plan to continue filing patents for technological innovations, including fundamental proposals for which we see a clear implementation route and possible exploitation paths. The team has been actively participating in the standardization of QKD, within the ETSI QKD Industry Standardization Group, on implementation security [573], the writing of the first Protection Profile for QKD, and by leading the initiative, as Rapporteur on QKD Deployment [575]. The recent work (portfolio P4) on a tight and general finite-size security proof for QKD, opens up interesting prospects not only in terms of standardization but also in the valorization of the expertise needed to operationally write the distillation stack of a given protocol in this novel framework.

13.4.3 Science popularization

In addition to scientific production and dissemination, the team has also produced articles and media material oriented toward the general public, as listed below:

- Article in Blog IM'Tech, Ordinateur Quantique et applications, April 2019.
- Article in La Recherche, La suprématie quantique de Google, vraie performance ou simple buzz ?, November 2019.
- Article in La Recherche, L'intrication quantique et l'espace-temps, July 2021.
- Article in Sciences et Vie, La Cryptographie défiée par le quantique, September 2021.
- Presentation to a delegation from the University of Hannover, on Quantum Research activities at QURIOSITY, March 2023.
- Invited talk to present QURIOSITY at Telecom Paris Journées Partenaires Entreprises, March 2023.
- Article: QURIOSITY : des données dopées au quantique, June 2023.
<https://www.inria.fr/fr/curiosity-donnees-quantique>
- Talk on Quantum Computing at MEDEF Essonne, at ENS-Paris Saclay, October 2023.
- Podcast: interview of Romain Alléaume, in DECODE QUANTUM, April 2022.
- Video + podcast, Telecom Paris Ideas, on quantum application, quantum networks and the challenge of scalability
<https://www.telecom-paris.fr/fr/ideas/informatique-quantique-echelle-applications>
- Romain Alléaume gave a talk "Nouvelles Quantiques de Telecom Paris", and participated in an invited panel at the Prix des Technologies Numériques, Oct. 2023.

13.4.4 Synthetic self-assessment

Strengths The team is visible as a result of its extensive partnerships and active interactions with socioeconomic partners, notably in the context of collaborative European projects.

Opportunity The project to create a new M2 in Quantum, Mathematics, and Informatics, and to federate forces from the Saclay ecosystem, will also be a great opportunity to strengthen the bonds with the French quantum industry in the field.

Chapter 14

Self-assessment of RMS Team

14.1 Profile, Resources and Organization of the Team

14.1.1 Scientific Objectives

The research themes of the Networks, Mobility and Services (RMS) team address the design, deployment and operation of large-scale digital communication infrastructures. Such a field raises specific scientific challenges that require the use of a plurality of tools, from theoretical modeling to testbed developments.

One major issue remains the accurate modeling of systems. The recent development of AI applied to networking seems to have reduced interest in such traditional modeling activities. Even though AI has provided interesting insights into how certain specific problems may be solved, the use and integration of AI in large-scale systems is extremely challenging and sometimes irrelevant. RMS intends to develop a wide range of modeling approaches to design efficient networks based on a plurality of tools.

The team members have made significant contributions to strategic infrastructures such as the Internet, cellular networks, data centers, cloud computing, public safety networks, and smart grid infrastructures. All these contributions have in mind their applicability in a large-scale infrastructure.

This is a major issue for French sovereignty, and more generally for all stakeholders using these infrastructures.

In particular, this involves designing tomorrow's mobile networks and communications, the Internet of the Future, the Internet of Things, and developments in cloud computing and virtualization. Our methodologies range from experimentation to theory: we build models and metrology tools, design architectures and protocols, and develop algorithms and mathematical analysis methods for performance evaluation and network optimization at the system level.

14.1.2 Resources

Team leader: P. Martins (until 2019), M. Coupechoux (2020-2021), L. Decreusefond (since 2022).

Faculty: S. Al Zahr (Associate Professor), N. Boukhatem (Full Professor), M. Coupechoux (Full Professor), L. Decreusefond (Full Professor, since 2021), M. Gagnaire (until 2021, Full Professor), D. Kofman (Full Professor), L. Iannone (until 2020, Associate Professor), K.-W. Lim (Associate Professor), L. Linguaglossa (since 2020, Associate Professor), P. Martins (Full Professor), D. Rossi (until 2018, Full Professor) J.L. Rougier (Full Professor), A. Vergne (Associate Professor).

Invited researcher: F. Baccelli (Full Professor, Académie des Sciences).

Emeritus: M. Gagnaire, P. Godlewski, N. Simoni.

Research engineers: A.K. Arif, J.S. Gomez, A. Rhmari Tlemcani, B. Arab, Tuan Anh Nguyen.

Laboratory: The team has extensive expertise in the design and operation of large-scale research platforms. It has been involved since 2009 in the FIT IoTLab Equipex project. Since 2019, it has also been an active member of the SLICES-FR project, which is the French national cluster of the ESFRI European program. RMS will actively contribute to the design and operation of SLICES-FR for 5G/6G and AI IoT use cases.

Current RMS Research platforms make it possible to perform experiments remotely at every level of a cellular system (RAN, Core Network) for a wide range of cellular technologies: 2G (GSM/GPRS/EDGE), 3G, LTE, NB-IOT, LTE-M, 5G NSA, 5G SA. Network entities can all be located inside a Faraday Cage for experiments in a fully protected environment. They can also be split between servers in a Faraday Cage (Access networks) and Télécom Paris data center (core network elements). Mobile Edge computing experiments can also be supported with dedicated embedded AI hardware. Most recently, RMS has also obtained a license from ARCEP to transmit in band B38. This network has been deployed on the roof of Télécom Paris to perform outdoor experiments for 4G/5G and IoT use cases. The last component of RMS research platforms is a metrology framework that can be used to monitor the system performance at every level of the system architecture and protocol stack. Specific sensors are also deployed to monitor received powers and to assess EMF exposure levels. Data generated by these different experiments can be retrieved remotely by users for further processing and investigation.

The RMS team is a member of the **LINCS** laboratory bringing together researchers from Nokia Bell Labs, Institut Mines Télécom, Inria, Sorbonne Université and SystemX. Today, LINCS comprises more than 100 senior and junior researchers, covering a broad range of research areas, both at the core of digital technologies and in relation to the digitalization of various activity sectors, such as energy, transportation and health. The members of LINCS are now hosted on our campus at Palaiseau.

The RMS team is a member of the **SEIDO** joint laboratory together with EDF R&D. The lab's topics cover cybersecurity and the Internet of Things, and the collaboration has been renewed for the period 2022-2026 for the third time. Since its inception in 2012, SEIDO's activities focused on all the aspects of trusted IoT for energy services, ranging from the deployment of energy efficiency services based on connected objects (electric vehicles, household appliances, etc.), to ensuring the coherence of the entire system and guarantee its security (access control, confidentiality, etc.). The laboratory applies a cross-cutting approach to the monitoring of hardware/software vulnerabilities and related security mechanisms, decision-making for risk management, and post-5G network systems. Within the SEIDO framework, several PhD programs, publications, and patents have been bootstrapped.

Financial resources The team benefits from different types of research funding from both national and international sources.

Type of contracts	Budget (K€)
European Contracts	500
ANR	1,200
Carnot	230
Bilateral contracts	847
Joint laboratories (CISCO & EDF)	2,300
Cluster Saclay	220
IPP (prématuration)	227
CIFRE PhD	15 grants

14.1.3 Team's functioning

Team meetings are held monthly. Some extra meetings take place for specific events, such as the recruitment of a new assistant professor or brainstorming about educational programs.

The team is sensitive to gender equality. It is currently the team with the best gender balance in the LTCL.

Following laboratory policy, the team is conscious of sustainable development issues. It notably limits travel when a virtual meeting is possible. The same applies to conferences, where local and virtual conferences are preferred, or the number of physical attendees is limited to one researcher.

14.2 Attractiveness

14.2.1 Scientific attractiveness

- Invitations: Invited talk IEEE SPCOM'22 (M. Coupechoux), Keynote speech GAMENETS'21 (M. Coupechoux), Keynote speech IEEE ACTS'20 (M. Coupechoux), Invited presentation IFIP/IEEE PEMWN'19 (M. Coupechoux).
- Organization of scientific events: TPC Co-Chair GAMENETS 2018 (M. Coupechoux), General Chair GAMENETS 2019 (M. Coupechoux).
- Editorial responsibilities, steering committees: Guest editor Annals of Telecommunications 2023 (M. Coupechoux), Guest editor Springer Mobile Networks and Applications 2021 (M. Coupechoux), INFORMS 2021 (L. Decreusefond)
- Best paper awards: Best paper award ICT4S 2023 (M. Coupechoux), excellent paper award IEEE ICUFN 2022 (M. Coupechoux), best paper award Algotel/Cores 2023 (PM).
- D. Kofman is one the three mainstays of the ANR program "PEPR 5G et réseaux du futur".
- P. Martins is a senior member of IEEE. He is the scientific coordinator of 5G/6G and AI IoT testbeds for the SLICES-FR national cluster on the Palaiseau site. He is also the scientific coordinator of the IMT SDR Lab. He is currently involved in several national research projects on 5G systems: BPI 5gmMTC, BPI PIEC, BPI constellation (5G NTN, CMA IMTFor5G+, and PEPR 5G. He is a member of the France 6G committee.
- M. Coupechoux is a member of the ARCEP expert committee on mobile networks. He is also a member of the ARCEP/ADEME expert committee on the environmental impact of ICT. He has been part of the expert panel (revue critique) in charge of the evaluation of the ADEME report assessing the environmental footprint of internet access in France in 2023. He is a member of the working group on networks of the Shift Project.
- RMS has strong links with major ICT stakeholders (Cisco, Huawei, Google, Nokia). Several of our colleagues even joined some of these companies to undertake research and standardization activities.
- RMS researchers are also involved in cutting-edge projects with very innovative startups and small-size companies (Amarisoft).

14.2.2 Team hosting policy

RMS has developed a global strategy for its team hosting policy. For long-term research issues, RMS has invited renowned researchers, both from academia and industry, to become associate professors. RMS has also developed partnerships with international research institutes (NCRL Nanjing China, SJTU China, IIT Bangalore India, NTU Singapore, KAIST Korea ...) to leverage scientific exchanges. RMS also develops its scientific expertise by regularly inviting researchers for sabbatical positions in the laboratory. The team has also hosted several national and international conferences on advanced topics: For instance, F. Baccelli recently organized a workshop on reconfigurable intelligent surfaces with high-profile speakers.

14.2.3 Calls for projects

RMS is involved in several national and European research projects to implement its strategic vision. Team members regularly answer calls for proposals both at national and European levels to support all our research activities: doctoral and postdoctoral contracts. RMS currently supports three research engineers using its own resources. RMS is also involved at the highest level in the PEPR "5G et réseaux du futur": D. Kofman is one of the three mainstays of the overall project. RMS members are also involved in almost all PEPR work packages, with different levels of responsibility. It provides us with significant scientific visibility, enabling us to contribute to the development of national (France 6G project) and European research strategies (SNS, SRIA European calls).

14.2.4 Synthetic self-assessment

The team's research topics cover a wide range of modern network technologies. We consider practical implementations as well as theoretical investigations which cross-fertilize each other.

Strengths We cover a wide range of topics from the most theoretical to the implementation of protocols through platforms. We operate a national and soon international open platform for 5G-6G mobile network experiences with a dedicated team of research engineers. We have high visibility at both national and international levels. We are involved at the highest level in several key projects (PEPR, SNS, etc.)

Weaknesses The average age of RMS members is high with a lack of young assistant professors. We are currently understaffed, which prevents us from participating in all the projects we possibly could.

Opportunities Both the European Community and the French authorities have recently decided to develop research on the future of telecommunication systems, notably the next generation of cellular networks 5G/6G. We are already involved in these projects thanks to the PEPR project, with D. Kofman, one of its three mainstays, as a member of the team. Another member is in the steering committee of the French 6G initiative.

Threats The local and international context in the period under review led to an underestimation of the importance of technological issues in France. RMS has been unable to recruit any new researchers since 2019. At the same time, three researchers left the team.

14.3 Scientific Production

Table 14.1 presents overall scientific production figures between 2018 and 2023. The detailed bibliography is listed in the dedicated accompanying document.

Journals	Articles in Proceedings	Books and Book Chapters	Patents	Habilitation thesis	Completed PhD
47	93	6	1	1	29

TABLE 14.1: Overall Scientific Production

14.3.1 Architectures, protocols and services for future networks

Protocols for mission-critical communications

Business- and mission-critical communications are communications between professional users either from the public safety sector or operating critical infrastructures. Owing to special coverage, priority access, reliability, and resilience requirements, as well as additional services for professional users, these communications are conveyed by Professional Mobile Radio (PMR) networks. Driven by the growth in demand, significant changes are taking place in the PMR industry. The existing PMR technologies are indeed not well suited to provide high data rate mobile services such as video and photo transfers. As a result, the adoption of commercial technologies for mission-critical communications is gaining strong momentum. On the other hand, the next-generation cellular networks are envisioned to support a broad variety of applications and services with heterogeneous performance requirements, i.e. enhanced Mobile BroadBand (eMBB), massive Machine-Type Communications (mMTC) and Ultra-Reliable Low Latency Communications (URLLC). Recently, mission-critical communications have been classified in a URLLC use case family, characterized by the need for higher priority over other forms of communication in networks. In this context, we focus on [665, 664, 663, 684, 682, 683], on enhancing the coverage of wireless networks providing group communications, the main service allowed by PMR networks, taking advantage of the current technologies (e.g. Multimedia Broadcast/Multicast Service), to meet mission-critical communication needs. First, we evaluate the performance of unicast and multicast transmission techniques, i.e. the Multicast/Broadcast Single Frequency Network (MBSFN) and Single-Cell Point-To-Multipoint (SC-PTM), in terms of radio quality, system spectral efficiency and cell coverage, assuming static MBSFN configurations. Then, we introduce an analytical model to derive an approximate closed-form formula of the Signal to Interference plus Noise Ratio (SINR) in an MBSFN network. Furthermore, we propose a simple repetition scheme without request, as an alternative to Hybrid Automatic Repeat Request (HARQ), to improve network coverage in the presence of group communications. By considering wireless channel characteristics, as well as service delay constraints, we show that our proposed scheme provides significant gains over traditional repetition schemes. Finally, we assess the trade-off in the cluster size of serving cells which arises between network coverage and capacity in multi-point transmissions. We formulate an optimization problem to maintain an acceptable system blocking probability while maximizing the average SINR of the multicast group users. For group calls, a dynamic cluster of cells is selected based on the minimization of a submodular function that takes into account the traffic in every cell through certain weights and the average SINR achieved by the group users. Traffic weights are then optimized using a Nelder-Mead simplex method to track a blocking probability threshold. Results show the importance of dynamic clustering in improving system capacity and coverage.

5G RAN: physical layer implementation and network slicing

A critical evolution from 4G to 5G is the heterogeneity of the terminals that connect the network. Those terminals range from smartphones to connected vehicles and sensors for agriculture. Given that the constraints and requirements associated with the different kinds of terminals are heterogeneous, it is important to multiplex the services associated with them on top of a single physical infrastructure. Network slicing is the technology that enables the physical infrastructure to provide multiple logical networks (called network slices) to serve the various devices and associated services: this work studies network slicing and its implementation at the RAN level. One main issue raised by network slicing is resource allocation. Indeed, many models exist for resource allocation of the RAN but we are missing models which take into account new constraints implied by network slicing. The first contribution of this research is to define a new model for network slicing at the RAN level. This model takes into account diverse slice constraints such as capacity, UE density, latency, and reliability. Simplicial homology is used to validate slice constraint fulfillment. Furthermore, this model is applied to power optimization, which is a critical aspect of network deployment. The second challenge addressed in this work is the network's supervision and control. Indeed, some verticals have ultra-high control requirements, and the network itself

might not be able to satisfy this constraint fully. Therefore, we introduce a probe that can extract data from the network to feed supervision tools for the network’s monitoring and control. This probe is designed to be resilient to cyber-attacks and is thus independent of the network. The last main contribution of this thesis is the introduction of an open-source 5G physical layer called free5GRAN. The physical layer provides all the minimal procedures and algorithms for communications between the gNodeB and UEs. The project’s structure is created so one can easily modify it and implement new features. Furthermore, the software architecture is designed so that the physical layer is modular and can be derived to implement the open-RAN split 7.2 [669][668][667]. We also address the problem of planning and dimensioning in radio access networks equipped with distributed edge servers. We propose a model that satisfies service requirements and makes use of network slicing and virtualization techniques. We showcase the advantages of using our holistic model to automate RAN planning by utilizing simulated annealing and greedy methods.

14.3.2 Virtualization and Automation in Network and Cloud environments

Towards network automation with telemetry and machine learning

Given the increased use of devices in networks¹ and the wide variety of services offered, network management and planning becomes extremely complex. More automated solutions at the element/device level are required. We propose a semi-automated framework called AI-driven telemetry (ADT) for collecting, processing, and assessing the state of routers using streaming telemetry data. ADT consists of 4 building blocks: collector, detector, explainer, and exporter. We concentrate on the detection block in ADT and propose a multi-variate online change detection technique called DESTIN. The detection method manages to perform well while maintaining low complexity (it is now on-boarded in Cisco XR IOS official releases). Our study on the explainer block of ADT consists in exploring the potential of the input data and showcasing the possibility of automated event description.

Distributed Storage

Distributed storage is an essential component of cloud and data center architectures. The team has several ongoing projects around this important topic.

In collaboration with Cisco, we propose 6Stor, an original architecture that uses a distributed layer of metadata based on IPv6 to provide flexible and scalable object-level storage. Benchmarks on real testbeds demonstrate significant performance and latency improvements over state-of-the-art legacy storage solutions (such as CEPH). We also show how to leverage the caching capabilities of regular storage servers when they are used to deploy distributed storage systems using erasure codes as their reliability mechanisms. Simulations show that locally handling data fragments such as traditional files on servers leads to non-optimal cache usage. A straightforward way to handle this problem is then proposed and its impact is evaluated.

We address the implementation of data coding solutions for distributed storage systems to provide data reliability in case of node failures. We propose new data coding schemes aimed at improving data recovery time and reducing the bandwidth and I/O repairs. This work led to an international patent and a proof of concept has been developed along with extensive tests to assess its performance improvements over existing solutions.

In addition, we focus on automatic data placement in distributed storage systems. Innovative machine learning solutions are used to automatically assign data to the appropriate storage elements. The aim is to provide flexibility thanks to the on-the-fly placement and the support of a multi-feature capability: based on the learning process, new data entering the system can be directly assigned to the appropriate storage device according to its characteristics. Additionally,

¹Some manufacturers estimate that the number of IP routers used in telco networks has multiplied by a factor of between 2 to 5 with the deployment of 5G networks for instance.

automatic placement provides reduced network utilization for data relocation. For this work, a patent has been filed and a proof-of-concept developed.

Both the aforementioned technologies for distributed storage systems have been supported by different sources of pre-maturation funding (Télécom Paris, IP Paris); their transfer for the creation of a Télécom Paris spin-off is under study.

Finally, we recently started working on distributed storage in "far edge" environments, i.e. the edge system which also encompasses users' devices (laptops, personal computers, local networks, etc.). This project is funded by Cisco. New architectures are required, particularly given the heterogeneity of devices in far-edge environments.

High-speed software networks and integrated machine learning tools

The landscape of modern network systems is experiencing a significant paradigm shift due to the widespread adoption of network softwarization [686]. Alongside the widespread diffusion of Network Function Virtualization (NFV) and cloudified network systems (e.g. cloudRAN), we observe a so-called compute-network convergence, referring to the integration or merging of traditionally separate computing and networking infrastructures into a unified architecture that can be easily adapted for future-proof networking systems. This is particularly evident as machine learning (ML) techniques are increasingly being applied within network applications for a variety of purposes, ranging from anomaly detection to performance prediction [702, 703].

While softwarized networks offer numerous advantages, the software data planes they rely on may not consistently deliver predictable performance [705, 685]. Moreover, a trade-off arises concerning the placement of the networking and compute functions (such as forwarding functions, integrated ML, or access control systems) where software measurements are also required. This trade-off involves the amount of data required to achieve a desired state of the system, which is in contrast with the performance of the system when high-speed traffic is present, which in turn requires additional resources (and therefore, additional energy).

In particular, software measurements require CPU cycles that are subtracted from the normal processing pipeline. Furthermore, when multiple software components coexist in the same infrastructure, they compete for the same underlying resources, which can potentially impact the performance of the whole system. Moreover, deploying multiple ML and data processing components may require additional servers to be activated to host the ML computation, thereby augmenting the energy footprint of the overall network applications.

Predicting performance is crucial for network operators to meet Service-Level Agreements (SLAs), particularly in high-speed environments such as Gigabit or Terabit Ethernet. It is essential to allow network operators to monitor their infrastructure without impacting the performance of the system, by developing novel techniques to provide a non-invasive monitoring methodology based on ML [703].

Furthermore, it is important to evaluate energy/performance trade-offs in such a system, to maintain a satisfactory quality of service and, at the same time, limit the amount of energy required for a desired QoS.

These topics are currently being investigated by the RMS team with the support of both individual grants (ANR JCJC, E4C) and projects for national funding (PEPR "Réseaux du futur", Projet Inter Carnot "Vers6G").

14.3.3 Models and algorithms for future networks

About models

Mathematical models provide insights into the systems to be designed or operated which can be useful for designing operational machine learning algorithms. Realistic models are frequently intractable, necessitating the sacrifice of certain phenomenological aspects for the sake of tractability. Continuing this line of research [662, 661], we focused on evaluating the error made by making some of these approximations [658, 659] for Markov models which are commonly used in telecommunications, epidemiology and many other fields. The mathematical framework used in these

papers is the core subject of the book [670]. We continue its development in papers such as [671] and [673].

When using stochastic geometry in the modeling of wireless systems (see below), beyond the classical Poisson point process, for engineering reasons we are often called upon to consider point processes with repulsive features. There is a trade-off between instances of these processes which are easy to simulate such as Matern-hard core processes and those whose mathematical properties are rich enough for a thorough mathematical analysis such as determinantal point processes. In [672], we used some of our previous results on optimal transport for point processes to quantify the error made by an approximate but efficient simulation algorithm of determinantal point processes instead of the exact but excessively slow method. We released an open-source code that can be used to simulate the realization of a Ginibre point process of ten thousand points in a few seconds where previous implementations would have taken hours.

Stochastic geometry models

Future wireless applications suggest that a sharp increase is likely in the number of use cases and services, which cannot be sustained by incremental improvements on existing communication schemes. Several candidate technologies have been evaluated and optimized using the mathematical framework of stochastic geometry.

In [676, 679, 678, 680, 677, 681, 675], we model and evaluate cellular networks consisting of multi-radio access technique (RAT) mm-wave small cells deployed on top of the legacy macro-architecture. First, we mathematically model a homogeneous deployment of multi-RAT small cells and characterize the user and network performance in terms of signal-to-interference plus noise ratio (SINR) coverage probability, downlink throughput, and cell overloading probability. Then, we study users' association to different tiers and the optimal selection of different RATs, to optimize these performance metrics. Generally, cellular network models that assume homogeneous deployments of small cells fail to take into account the nuances of urban blockage characteristics. To address this, we model small cell locations along the roads of a city, and subsequently, take into consideration signal blockages due to buildings or moving vehicles on the roads. In this network, we assume that the operator supports three types of services: ultra-reliable low-latency communications (URLLC), massive machine-type communications (mMTC), and enhanced mobile broadband (eMBB) with different requirements. Consequently, we study the optimal RAT selection for these services using varying vehicular blockages. Finally, based on the on-road deployment model of mm-wave small cells, we study a network designed to support positioning and data services simultaneously. We characterize the positioning accuracy based on the localization bounds and then study optimal resource partitioning and beamwidth selection strategies to address varied positioning and data-rate requirements.

In [654, 656, 655], we study Full-duplex (FD) technology. Full-duplex is a principle in which a transceiver can receive and transmit on the same time-frequency radio resource. The principle was long considered impractical due to the high self-interference that arises when simultaneously transmitting and receiving in the same resource block. When assuming perfect self-interference cancellation, FD can potentially double the spectral efficiency (SE) of a given point-to-point communication. In practice though, it is not possible to achieve the aforementioned characteristic. Moreover, in a cellular network context, not only self-interference limits performance, since additional co-channel interference is created by base stations (BSs) and user equipment (UEs). However, even with higher interference, downlinks (DLs) still obtain higher SE performances, whereas uplinks (ULs) are generally critically degraded, when compared to half-duplex (HD). We focus our work on the study of alternatives that can help improve impaired ULs in FD networks, while still seeking to benefit from the gains experienced by DLs. In this regard, we use stochastic geometry as a means to characterize key performance indicators of cellular networks, such as: coverage probability, average SE, and data rates. Firstly, we propose a duplex-switching policy that enables BSs to operate in FD- or HD- depending on the UL and DL conditions. Secondly, we investigate the performance of hybrid HD/FD networks in a millimeter wave context. Finally, we propose a novel algorithm based on non-orthogonal multiple-access (NOMA) and successive

interference cancellation (SIC), which allows BSs to coordinate on their respective transmission schemes to reduce BS-to-BS interference. We demonstrate that the models facilitate a balancing of the gains of one link over the other; reducing UL degradation, while maintaining DL gains. In addition, we show that scenarios in which equipment can perform beamforming are ideal for FD deployments since they directly reduce the co-channel interference.

Device-to-device (D2D) communication is a key technology for future wireless and cellular networks, allowing devices to communicate directly without relying on a cellular infrastructure. This makes D2D a promising technology for Ultra-Reliable Low Latency Communications (URLLC). Millimeter wave (mmWave) D2D communication is a technology that uses high-frequency radio for direct communications between devices, offering very large bandwidths for fast and reliable transmissions. However, mmWave frequencies have high attenuation, requiring devices to be fitted with multiple antennas and perform beamforming to enhance signal strength and quality. The success of beamforming requires beam training. Misalignment errors can occur within the training process, leading to a degradation of data transmission performance. To address these challenges, our studies [695, 694, 693, 692] focus on the theoretical analysis of the performance of mmWave D2D communication in terms of latency, reliability, and coverage in the context of URLLC. We use stochastic geometry and queuing theory to evaluate both spatial and temporal variations in performance from two different perspectives: the instantaneous average properties of the random network and the global ergodicity properties of a dynamic network with random service requests. We consider a dynamic D2D communication model where transmitters and receivers have multiple antennas and adopt beamforming for the dynamic case. The network is dynamic since there are random arrivals of new D2D devices. Moreover, users who finish communications leave the network immediately. In this way, a continuous spatio-temporal model for the wireless network is established, which combines a spatial stochastic point process and a dynamic birth-death process. This process is referred to as the spatial birth-death process. The application of this model to the D2D network was first studied by Sankararaman and Baccelli in 2017. We extend the results of Sankararaman and Baccelli with regard to the stability condition of such a network by introducing directional antenna arrays for the D2D users. We use an analog beamforming model based on a uniform linear array (ULA). Since the beams are narrow, beam misalignment can dramatically reduce the performance of the network. Thus, the evaluation of the impacts of misalignment is performed by assuming a statistical alignment error distribution. For the instantaneous properties, we are mainly concerned with the reliability of the communication. In the context of URLLC, the reliability of a network refers to the likelihood that the communication latency is lower than a certain threshold, given that the network is under a specific random process. Traditionally this indicator can be calculated as the coverage probability, by considering a typical user under Palm distribution, which may lack information with respect to the diversity of devices. Then meta-distribution is proposed as a novel metric that accounts for the spatial distribution of coverage probability. We study this metric for a D2D communication network with beamforming, where both transmitters and receivers are equipped with directional antenna arrays. The impacts of misalignment are first evaluated by assuming a statistical alignment error similar to the dynamic case. Then we investigate beam misalignment induced by the beam training method and channel conditions. Our studies show that there is a fundamental trade-off between training overhead and data transmission reliability. Finally, we derive the meta-distribution of the effective rate as a statistical latency guarantee for URLLC communications, by considering both the training overhead and misalignment. Results show that there is an optimal number of antennas for URLLC communications.

Stochastic and physical modeling of the indoor 5G millimeter wave propagation and future 5G/6G bands

5G millimeter wave (mmWave) use for transmission is challenging due to the propagation properties of this band. Transmission can be severely affected by diffusion effects, leading to an emergent major challenge: indoor coverage. This requires new studies to address three major issues: the im-

impact of environment geometry (apartment, factory, etc.) on indoor mmWave propagation, the impact of the various materials in the environment (concrete, plasterboard, etc.) on indoor mmWave propagation and what planning methods should be used for the various indoor 5G applications (fixed wireless access, industry 4.0, etc.). These challenges can be addressed through a novel theoretical framework that combines stochastic indoor environment modeling with advanced physical propagation simulation. This approach is specifically adapted to investigate indoor-to-indoor 5G mmWave propagation. Its system implementation, so-called iGeoStat, generates parameterized typical environments that account for indoor spatial variations, then simulates radio propagation based on the physical interaction between electromagnetic waves and material properties. This framework is not dedicated to a particular environment, material, frequency or use case and aims to statistically understand the influence of indoor environment parameters on mmWave propagation properties, especially coverage, SINR, and path loss. iGeoStat's system implementation raises numerous computational challenges that are solved by formulating an adapted link budget and designing new memory optimization algorithms [688][689].

The first simulation results for two major 5G applications (fixed wireless access and industry 4.0) are validated with measurement data and show the efficiency of iGeoStat to simulate multiple diffusion in realistic environments, within a reasonable amount of time and memory resources. Generated output maps confirm that diffusion has a critical impact on indoor mmWave propagation and that proper physical modeling is of the utmost importance to generate relevant propagation models. Using iGeoStat, the main propagation parameters are investigated in various scenarios, showing that the complex refractive index of the indoor material has a moderate impact on the received power, while its surface roughness parameter has a major impact and may completely change the power profile in the environment.

Resource allocation optimization

Non-orthogonal multiple access (NOMA) is a promising technology for increasing spectral efficiency and enabling massive connectivity in future wireless networks. In contrast to orthogonal schemes, such as OFDMA, NOMA can serve multiple users on the same frequency and time resource by superposing their signal in the power domain. One of the key challenges for radio resource management (RRM) in NOMA systems is to solve the joint subcarrier and power allocation (JSPA) problem. In [699, 701, 700, 698], we present a novel optimization framework to study a general class of JSPA problems. This framework employs a generic objective function that can be used to represent the popular weighted sum-rate (WSR), proportional fairness, harmonic mean, and max-min fairness utilities. Our work also integrates various realistic constraints. Using this framework, we prove that JSPA is NP-hard to solve in general. In addition, we study its computational complexity and approximability in various special cases, for different objective functions and constraints. In this framework, we first consider the WSR maximization problem subject to cellular power constraint. We propose three new algorithms: OPT-JSPA computes an optimal solution with lower complexity than current optimal schemes in the literature. It can be used as an optimal benchmark in simulations. However, its pseudo-polynomial time complexity remains impractical for real-world systems with low latency requirements. To further reduce complexity, we propose a fully polynomial-time approximation scheme called ϵ -JSPA, which allows tight trade-offs between performance guarantee and complexity. To the best of our knowledge, ϵ -JSPA is the first polynomial-time approximation scheme proposed to address this problem. Finally, GRAD-JSPA is a heuristic based on gradient descent. Numerical results show that it achieves near-optimal WSR with much lower complexity than existing optimal methods. As a second application of our framework, we study individual power constraints. Power control is solved optimally by gradient descent methods. Then, we develop three heuristics: DGA, DPGA, and DIWA, which solve the JSPA problem for centralized and distributed settings. Their performance and computational complexity are compared through simulations.

Bidding strategies for spectrum auctions

Since its introduction in 1994 in the United States, the simultaneous ascending auction (SAA) has been the preferred mechanism for auctioning licensed spectrum. It has recently been used in several countries, including Germany, Portugal, and Italy, for the allocation of 5G frequencies. Furthermore, this mechanism will likely play a central role in the 6G frequency allocation process taking place around 2030. Given the amounts invested, sometimes exceeding a billion euros, and the strategic implications determined by the results of these auctions, it is fundamental for mobile operators to establish an effective bidding strategy.

Despite the importance of this issue, we observe that there is a lack of research dedicated to developing an effective bidding strategy within SAA. This gap is partly explained by the intrinsic complexity of the game associated with the SAA auction, making its analysis using auction theory too difficult, in addition to the application of exact game resolution methods. Furthermore, this particular mechanism gives rise to various strategic problems, such as the exposure problem, adding an additional layer of complexity to its study.

In [690], we propose the use of Monte Carlo tree search (MCTS) to calculate an efficient bidding strategy within the SAA. To develop such an algorithm, we have gradually made our SAA model more complex. First, we modeled the SAA auction as a sequential N-player game with perfect and complete information, with numerical experiments carried out on small instances. Then, we modeled the SAA auction as a simultaneous N-player game with full information, with budgetary and eligibility constraints, and the numerical results were obtained on real-sized instances. Finally, we considered the previous game in its incomplete information version to model the different uncertainties present in reality. For each of these three models, we propose an algorithm that largely outperforms other algorithms in the literature. Our algorithms notably obtain greater utility by better handling the various strategic problems of SAA such as the exposure problem. In addition, we develop a method for predicting final prices on which our MCTS algorithm relies.

Reinforcement learning for URLLC

In [697, 696], we explored the application of Deep Reinforcement Learning (DRL), both from a single-agent and a multi-agent perspective to develop efficient transmission protocols within an industrial IoT environment, under the stringent constraints of URLLC. Indeed, traditional Multiple Access (MA) protocols struggle with several significant challenges when dealing with URLLC requirements. On the one hand, despite their effectiveness in device coordination and avoiding collisions, centralized protocols, are hindered by significant communication overhead and the resultant latency from the coordination process. On the other hand, GF protocols, although promising alternatives for URLLC due to their ability to bypass the latency of traditional four-way handshake protocols, face collisions. Additionally, the current protocols are not tailored to handle diversity in devices and the sporadic nature of traffic in dynamic environments. These works aim to address such challenges through the innovative application of DRL strategies. Our research initially focuses on a framework modeling the uplink MA problem as a centralized problem where the BS schedules devices to prevent collisions. To minimize latency, we eliminated the usual coordination communications between devices and the BS, a move that introduced partial observability into the system. We address this problem by developing FilteredPPO, a novel scheduling algorithm. By integrating PPO with RNN and invalid action masking, FilteredPPO demonstrates superior performance over conventional benchmarks in scenarios with periodic traffic. As FilteredPPO struggles to meet the URLLC requirements under aperiodic traffic, we extend our scheduling framework by incorporating the NOMA technology, allowing the BS to poll multiple users within a single frame. We introduce the concept of agent state, to better manage partial observability and develop NOMA-PPO, a DRL algorithm that efficiently deals with the combinatorial action space using a branching policy network and can incorporate prior knowledge about the system evolution through a Bayesian prior. Our experiments, conducted under realistic 3GPP conditions confirm the effectiveness of NOMA-PPO in terms of URLLC performance, fairness, and convergence speed, outperforming traditional MA and DRL benchmarks across various scenarios. We then move to

the decentralized version of our MA problem and explore the application of deep MARL to tackle it, leading to the creation of SeqDQN. This distributed MARL algorithm updates Q-functions sequentially, starting with devices having the strictest latency requirements. SeqDQN presents advantages in scalability and training speed over traditional MARL approaches and reduces non-stationarity issues. Finally, we extend the decentralized framework by efficiently utilizing the bandwidth through orthogonal channel division. This transforms our URLLC problem into a Distributed Multiple Channel Access (DMCA) problem with heterogeneous devices. We solve it by proposing two PPO solutions: MCA-PPO and MCA-iPPO. While MCA-PPO offers a theoretically grounded approach with monotonic improvement guarantees, MCA-iPPO provides a decentralized, empirically effective alternative with a simpler training process. We show that our approach outperforms the existing MA and DRL benchmarks on different scenarios.

14.4 Contribution of Research Activities to Society

14.4.1 Socio-economic partnerships and interactions

Interactions with members of the French Parliament: Audition at the Sénat Office Parlementaire d'Évaluation des Choix Scientifiques et Techniques 2018 (M. Coupechoux), with members of the European Parliament: Audition at AIvolution Seminar European Parliament 2023 (M. Coupechoux).

The RMS team actively contributed to the development of the scientific project for the SEIDO Lab. In particular, after the renewal of the joint lab, the scientific project has been enriched by introducing the topic of 5G and next-generation networks. RMS is also a member of the operational committee and the steering committee of SEIDO, with a co-coordination function (definition of research direction, identification of partners) and industry/academia mediation. RMS also has a budget management role (S. Al-Zahr until 2023, L. Linguaglossa ongoing). Such interaction is also intended to involve EDF researchers who will participate in Télécom Paris classes in the coming years.

14.4.2 Products for the cultural, economic and social world

Some of us (M. Coupechoux) are involved in the analysis of the ecological impact of telecommunication networks, including participation in the Shift project conference on digital sobriety.

14.4.3 Science popularization

M. Coupechoux is regularly invited to give public presentations, as well as interviews in the media and has published articles on the environmental impact of 5G, networks and ICT.

- Public presentations: Champagne au Mont d'Or 2021 (M. Coupechoux), Association Lire c'est Vivre prison de Fleury-Mérogis 2023 (M. Coupechoux)
- Media: Tribune Le Monde 2020 (M. Coupechoux), Tribune Reporterre 2020 (M. Coupechoux), paper Revue Télécom Alumni 2021 (M. Coupechoux), paper Revue Télécom Alumni 2023 (M. Coupechoux), Interviews in Le Monde Diplomatique 2020 (M. Coupechoux), Challenge 2020 (M. Coupechoux), EcoRéseaux Business 2020 (M. Coupechoux), Telerama 2023 (M. Coupechoux), La Croix 2023 (M. Coupechoux), Décryptages RFI 2018 (M. Coupechoux), La Méthode Scientifique France Culture 2021 (M. Coupechoux), La Terre au Carré France Inter 2023 (M. Coupechoux).

The RMS team contributes to the scientific animation of the yearly SEIDO workshop (S. Al Zahr until 2023, L. Linguaglossa in 2024). The workshop has recently introduced a more public-oriented and popularizing aspect, as the general public is not necessarily fully informed and up to date with respect to current developments in 5G+ networks and cyber security. The workshop features keynotes by recognized scientists or industry professionals identified through the mediation of the

RMS team. This workshop is also an opportunity to identify topics of general interest, such as digital sovereignty in 2021, and networks of the future in 2024.

L. Linguaglossa co-organized the 2022 edition of the Cloud/Edge Days (in French: *Journées Cloud/Edge 2022*, <https://journeescloud2022.wp.imt.fr/>). Since 2014, the working group Networks and Distributed Systems (GdR RSD) has been organizing Cloud Days to bring together French academics and industry employees to present topics related to the administration and use of virtualized/cloud environments. The 2022 edition featured the introduction of edge environments and saw the involvement of more than 40 participants (the majority of whom were based at Palaiseau), 2 invited keynotes, and 12 accepted communications (over 16 received submissions).

L. Linguaglossa has also been interviewed by Télécom Paris Ideas, a scientific communication platform launched by Télécom Paris, which focuses on publishing scientific content to be popularized in various formats targeting a broad audience. In 2023, the interview focused on the energy/performance trade-off and carbon footprint of high-performance network systems.

Chapter 15

Self-evaluation of IMAGES team

15.1 Profile, Resources and Organization

15.1.1 Scientific objectives

The activity of the IMAGES team covers many aspects of the processing, analysis and synthesis of digital images, volumes, and videos. A particularity of the team's work is controlling the entire image chain, from modeling the acquisition system to specific knowledge of the application domains. Another common point of much of the research carried out by the team is the use of mathematical modeling, with a particular focus on stochastic modeling, optimization and more recently machine learning. Indeed, over the period covered by this report the team's activity has been marked by a strong shift toward deep learning approaches, with a particular interest in developing methods capable of handling scarce or corrupted data, designing methods for specific imaging modalities, or understanding and structuring generative models. The main applicative fields in which the team's activity is focused are: remote sensing imaging, medical imaging, computer graphics, and natural image processing.

Medical imaging In medical imaging, one of our team's main specificities is the development of novel AI, image analysis and image understanding methods inspired by clinical experts' reasoning and driven by the needs and constraints expressed by our clinical or industrial partners. In particular, we strive to develop methods that are both explainable to clinicians as well as fair and robust to data biases, such as gender or acquisition sites.

Remote sensing imaging The team is developing innovative deep learning methods exploiting the specificities of imaging systems (physics of the acquisition process, complex valued data, multi-temporal series, etc.) for a wide range of applications, in particular for environmental or defense purposes.

Computer graphics Activities in computer graphics aim to develop a set of methods and tools for efficient and effective digital content creation. We focus in particular on physics-based and data-driven methods for fluid and deformable body simulations as well as artistic manipulation tools for 2D images and geometries.

Image processing/Computer vision The team has a longstanding interest in the mathematical modeling of natural images and textures, which over the period under review has evolved toward deep generative models. Understanding and structuring such models is a major concern of the team, with applications for image and video restoration, editing and synthesis.

The IMAGES team's research activity is conducted as part of a wide range of collaborations, with both academic and industrial partners. National academic collaborations include French grandes écoles and universities (Sorbonne Université, Université Paris Cité, Université Lyon 1, Université Saint-Etienne, Université Dauphine-PSL, ENS Paris Saclay, Ecole Polytechnique, Université de Bordeaux, Université Toulouse III, etc.), and research institutes (Inria, CNRS, IRCAM, Onera, CNES, Cesbio, Institut Pasteur, etc.). International collaborations include institutions such as TU Munich, Bundeswehr Universität München, TU Wien, University of São Paulo, University

of Tokyo, University of Santander (Colombia), University of the Andes (Venezuela), Columbia University, Harvard University, Cincinnati University, Technion, Korea University, IIT Madras, SupCom Tunis, University of Rome, University of Trento, Imperial College London, the Arctic University of Norway, among others. The team has also developed a number of industrial collaborations with partners in its main applicative fields (Interdigital, Valéo AI, L'Oréal, Incepto, Philips, Guerbet, MilVue, GE HealthCare, DxO, Imagine Eyes, etc.). In connection with its biomedical activity, the team collaborates with numerous hospitals and practitioners (Bicêtre, Necker Enfants Malades, Sainte-Anne, Pitié-Salpêtrière, Lariboisière, Robert Debré, XV-XX, Cochin, HEGP).

15.1.2 Resources

Team leader: Yann Gousseau, since January 2021, previously Florence Tupin.

Faculty: Elsa Angelini (Professor, since September 2021, previously on leave at Imperial College London), Isabelle Bloch (Professor, until December 2020, now on leave at Sorbonne University), Tamy Boubekeur (Professor, until September 2019, now at Adobe Research Paris), Pietro Gori (Associate Professor), Yann Gousseau (Professor), Christophe Kervazo (Associate Professor, since October 2020), Saïd Ladjal (Associate Professor), Loïc Le Folgoc (Associate Professor, since September 2022), Arthur Leclaire (Associate Professor, HDR, since September 2023), Henri Maître (Emeritus Professor), Alasdair Newson (Associate Professor, HDR, from June 2018 until August 2023, now on leave at Sorbonne University), Jean-Marie Nicolas (Professor, until March 2019, now retired), Amal Dev Parakkat (Associate Professor, since September 2021), Michel Roux (Associate Professor), Yohann Tendo (Associate Professor, until December 2019, now at ECE Lyon), Jean-Marc Thiery (Associate Professor, until August 2021, now at Adobe Research Paris), Florence Tupin (Professor, Head of the IDS department), Kiwon Um (Associate Professor, since October 2019).

Associate professors: Isabelle bloch (since 2021), Loïc Denis (since 2021).

Equipment - Computing facilities Learning-based approaches are present at all levels of team activity, which implies strong computational needs. These are mostly covered through pooled local computing facilities (LTCI/IDS cluster) and at the national level through the Jean Zay supercomputer.

Financial resources There is no recurrent team funding by our institution. Funding for team activities is obtained through diverse sources: national calls for projects (e.g. ANR projects), European funding (e.g. Marie Curie funding), local PhD funding (Télécom Paris, IP Paris), and CIFRE PhD funding, bilateral funding.

A non-exhaustive list of funded projects include: ANR projects such as PI (ALYS 2016-2020, ASTRAL 2022-2026, STAP 2018-2022, JCJC IDeGeN 2021-2024, JCJC SketchMAD 2023-2027) or as partner (Mistic 2019-2025, RHU TRT-cSVD 2017-2024), project Digicost MetaTracts (2017-2020), CIES funding (ALIA 2023-2027), European Project Horizon AQTIVATE (2023-2027), NIH US programs as partner (2014-2023, 2021-2025), IP Paris prematuration projects (6 projects over the period), PHC Aurora France-Norway (2021-2023), Medical Research Council project, UK (2020-2023), Imperial Biomedical Research Centre project (2023-2026).

Beside local PhD funding (at Télécom Paris, IMT or IP Paris level), other sources of PhD funding include CIFRE theses (Valeo, Kanop, Interdigital, Incepto, Guerbet, General Electric, Philips, L'Oréal, Skairos, etc.), funding from the CNES, AID and Onera, by DIM RFSI, as well as via international PhD programs (CSC China, Colciencias Colombia, etc.), among others.

15.1.3 Human resources management, safety, environment, ethical protocols, data and scientific heritage protection

Various meetings are regularly organized at team level: weekly team meetings, weekly PhD student reading groups, monthly scientific seminars, annual welcome day for new PhD students, various smaller working groups (remote sensing, biomedical imaging).

The team has a PhD student council with representatives and monthly meetings, whose role is to gather suggestions and make note of difficulties as well as prevent the social isolation of PhD students. We believe that this council was particularly important during the pandemic.

Gender equality could be improved at team level; the current proportion of permanent female team members is 2 out of 10.

The team is active in the organization and participation in the first working group on environmental issues at laboratory level (in 2023). As a result, it has been proposed (and currently under discussion) that each team should have an environmental representative to monitor and record environmental impact, in particular to mitigate the use of long-haul flights.

15.1.4 Synthetic self-evaluation

Strengths The team’s activity covers the full range of the imaging chain, from sensors to image interpretation. From a methodological point of view, over the period covered by this report, the whole team has undergone a fundamental evolution toward deep learning while keeping its strong expertise in the fields of image modeling and applied mathematics. We also believe that the team maintains a good balance between methodology and applications, which results both in high-quality publication records and a high number of industrial and societal partnerships. This activity has been strengthened by the successful recruitment of very promising young researchers and talented PhD students.

Weaknesses The number of HDR permanent members in the team is slightly insufficient with respect to PhD supervision, but this is currently being improved both by forthcoming HDR defenses and our most recent recruitment.

Opportunities Image enhancement, content generation and image understanding have attained a prominent position in our society, from everyday smartphone use to a massive automation in the treatment and analysis of images. The many successes of deep learning in these fields are of course instrumental in this development. In this context, there is an increasing need for applications in the fields of biomedical imaging, remote sensing imaging, digital photography and mass entertainment, all fields covered by the team’s activity.

Threats For the same reason, the team is in direct competition with industry, which results in the significant risk of potentially losing team members, a risk exacerbated by a loss of attractiveness subsequent to our move to Palaiseau. Two very active senior members (I. Bloch and T. Boubekeur) have left during the period covered by this report. These losses have fortunately been mitigated by highly successful junior recruitment over the period.

15.2 Attractiveness

15.2.1 Scientific reputation and contributions

The team publishes its research outcomes in high quality journals and conference proceedings, corresponding to various scientific communities: remote sensing, biomedical imaging, mathematical imaging, computer graphics, image processing, computer vision. Its members are regularly invited as speakers to national and international scientific events. A non-exhaustive list includes :

- Organization of scientific events: co-Chair for Special Sessions of the IEEE ISBI conference (2024), co-Chair for Finance of the IEEE Int. Ultrasonics Symposium (2022), co-Chair of the IEEE SPS-EMBS Summer School on Biomedical Imaging, tutorial for InGARSS conference (2022), organizer of workshop Statistics and Machine Learning at Paris Saclay (2023), etc.

- Editorial responsibilities:

Journals: 2016-2022, Journal of Spatial Science (F. Tupin, associate editor), Member of the journal Awards Committee of the IEEE Geoscience and Remote Sensing Society (F. Tupin), 2022-present, Medical Image Analysis journal (E. Angelini and I. Bloch, associate editors), 2020-present, Biological Imaging journal (E. Angelini, funding executive editor), 2023-present, Journal of Mathematical Imaging and Vision (I. Bloch and Y. Gousseau, associate editors), 2018-present, Image Processing Online (Y. Gousseau, associate editor).

Conferences Area chair Fuzzy Sets and Systems, Area Chair in Shape Space Session at GSI 2019, Area Chair of IJCAI and ECAI, Eurographics 2024 industrial track chair, Pacific Graphics 2022 Short Paper chair, Steering committee of DGMM and LFA conferences, various program committees (Eurographics, Pacific Graphics, Shape Modeling International, SIGGRAPH Asia Technical Communications and Posters, Computer Graphics International, CyberWorlds, Computer Graphics & Visual Computing, SCA, Grets).

- Participation in research steering bodies and evaluation committees:

Team members regularly participate in recruitment panels for associate professors, full professors, and senior researchers (at ENS Paris Saclay, CentraleSupélec, Centrale Lille, Inria, Télécom Sud Paris, TUM, Fondazione Bruno Kessler, etc.). They participate in the scientific boards of Inria, IRCAM, EPITA, IGN and CNRS CID55 and the Council of Engineering Faculty at UPMC (Pierre and Marie Curie University). They have also formed part of HCERES evaluation committees, the steering committee of E4Health, and the scientific advisory board for ISCETS (Portugal), IHU Lyric (France). They participate in fellowship and prize committees in France, Belgium and Spain.

- Prize winners:

Isabelle Bloch was awarded the Médaille de l'Académie des Sciences and the Prix Galien (together with Sabine Sarnacki). Several papers won prizes, including the IEEE GRS Society Symposium Prize (2021), the 2nd place Student Paper Award of EUSAR (2022), the CFPT best paper award (2018), best student paper at CVPR workshop (2019), best paper WBIR (2022), best oral presentation at MICCAI workshop (2023). PhD theses produced by the team were also distinguished: first PhD Award of Fondation Mines-Télécom (S. Lobry, 2018), accessit for the PhD Prize of IDIA Department at IP Paris (E. Dalsasso, 2023).

15.2.2 Staff hosting policy

The team has hired 6 new permanent researchers over the period, to mitigate the effect of a relatively strong turnover, in part due to the school's move to Palaiseau. In all cases, there was a significant number of good candidates and the candidates ranked first accepted the position. On the whole, recruitment was mostly exogenous (5 out of 6) and two candidates were non-French. The team aims to offer the best working conditions to newly arrived personnel, including a reduced teaching load in the first years, an arrival financial package of 10,000 euros, and co-supervision of PhD theses whenever possible.

The team also hosts a large number of talented young PhD students, including a relatively large number of ex-students from Télécom Paris (up to 5 at the same time). An annual welcome day is organized and monthly meetings are organized between the team leader and PhD representatives.

15.2.3 Success in competitive calls for projects

Most of the funding for team activity comes from successful answers to competitive calls which are very diverse: national, European, public, bilateral. A non-exhaustive list of such successes is:

- ANR projects : (PI for ALYS 2016-2020, ASTRAL 2022-2026, STAP 2018-2022, JCJC IDeGeN 2021-2024, JCJC SketchMAD 2023-2027, partner for Mystic 2019-2025, RHU TRT-cSVD 2017-2024), project Digicosm MetaTracts (2017-2020)

- European project AQTIVATE (interdisciplinary training program, 2023-2026)
- CIES project ALIA (2023-2027)
- project Medical Research Council UK (2020-2023)
- NIH US programs as partner (2014-2023, 2021-2025)
- PhD grants from numerous national sources (Télécom Paris, IP Paris, IMT, Hi! PARIS, AID, Onera, CNES, regional DIMs, UPSa IDI, etc.) and international calls (CSC China, Colciencias Colombia)

15.2.4 Synthetic self-evaluation

Strengths The team has a strong national and international recognition in the different communities it is involved in. Its attractiveness is reflected both by the recruitment of young researchers and the quality of its PhD students. The team is also very active in demanding and prestigious master programs such as the MVA master.

Weaknesses As previously mentioned, the departure of very active senior researchers is to some degree a reflection of a loss of attractiveness. The team's research activity would also benefit from partnerships with national research institutions.

Opportunities Merging research forces operating at the perimeter of artificial intelligence at the scale of IP Paris certainly is a strong opportunity, both in terms of visibility and for the mutualization of computing and human resources.

Threats The team's activity results in a very high demand for computing resources, but we should be careful when dealing with themes covered by companies or institutions whose computational resources are greatly superior to ours.

15.3 Scientific Production

15.3.1 Qualitative analysis

Medical Imaging Since 2015, activities in medical imaging have mainly taken a turn toward deep learning (starting with the PhD by H. Bertrand + collaboration with Philips [357]), while maintaining a solid grounding in mathematical models for image analysis and understanding, as well as structural and symbolic approaches. Machine and deep learning methods have been developed for various image analysis and interpretation tasks: reconstruction, registration, segmentation, object recognition, image generation and classification.

One specificity of our work is the development of new methods and deep learning architectures inspired by clinical experts' reasoning or driven by clinical needs or constraints.

For instance, we introduced topological and geometrical constraints into deep learning models for: 1) vessel segmentation (PhD by A. Virzi [473, 434, 472, 471, 470], C. Muller [436, 435, 437, 438, 439, 439] and G. La Barbera [412, 415, 411, 413, 414]); 2) increasing the sensitivity of segmentation methods at the extremities of elongated structures, such as the pancreas, which is a notoriously complicated area (CIFRE PhD by R. Vétel [467, 469, 468]); and 3) image registration of images with different topology, such as a healthy image and one with a tumor (PhD by M. Maillard [402, 423, 422] and A. François [392, 391]+ Collaboration with St. Anne hospital and MAP5 laboratory).

We also developed new self-supervised, contrastive learning methods to: 1) leverage clinical meta-data, such as age and sex, or known biases (e.g. site-effect, gender) to improve learnt representation (PhD by B. Dufumier [386, 387, 388], C.A. Barbano [481, 354], R. Louiset [421] + Collaboration with NeuroSpin, CEA and University of Torino); or 2) take into account multiple, partial and

inconsistent expert annotations, which are very common in clinical data-sets (CIFRE PhD of C Ruppli [458, 460, 459], E. Sarfati [462, 461]). These methods were developed for accurate and unbiased subject-level predictions in different applications (e.g. disease, tumor, lesion).

Generative models were developed to 1) improve transfer learning of segmentation models learnt on (big) adult imaging datasets to (small) pediatric datasets [414]; and to 2) generate missing imaging modalities in multi-modal segmentation (PhD by G. la Barbera) [413]. Generative models were also developed for style transfer and neural rendering (PhD by R. Kips + collaboration with L'Oréal [406, 407, 408, 409, 410]).

New representation learning models were also developed to 1) distill the knowledge of a multi-modal segmentation model towards a single-modal one (PhD of M. Maillard) [402] and 2) separate pathological from healthy patterns using contrastive analysis (Post-doc F. Carton and PhD of R. Louiset). Multi-modal segmentation was also addressed for liver and liver tumor detection and segmentation, when images are paired but not registered, with a method to enforce a constraint of similarity of predictions into learning, along with a method to interpret medical image segmentation networks (PhD by V. Couteaux [370, 374, 373, 371, 372]+ collaboration with Philips).

Our work on the modeling of spatial relations [361] was pursued, on the one hand by studying to what extent neural networks implicitly use these relations to recognize objects in particular spatial configurations (PhD of M. Riva + Collaboration with St. Paulo University and PSL-Université Paris-Dauphine [457, 455, 456]), and on the other by integrating them into logical reasoning formalism for spatial reasoning [358, 359, 360]. In addition, work on logic was developed in a much more general framework, proposing abstract logic in topos (collaboration with MICS Lab, CentraleSupélec, and CRIL, Université d'Artois) [352]. An emblematic application of this work is the segmentation and recognition of fiber vessels (brain white matter, pelvic nerves) from tractograms computed on diffusion MRI images. The original approaches proposed combine geometric modeling of the fibers (efficiently to facilitate their visualization, PhD by C. Mercier [430, 431, 381, 463, 429] + collaboration with LIX), and spatial relationships to other structures, by modeling anatomical knowledge of these fibers. Individual 3D models of patients are thus constructed, integrating organs, pathologies, blood vessels and nerves, for example, and are used to aid surgical planning (PhD thesis by A. Virzi, C. Muller, G. La Barbera + Collaboration with Hospital St. Anne, Necker Hospital and Philips). This work is now entering a valorization process, in order to foster a more extensive dissemination and adoption.

On the reconstruction side, collaborations with the Gordon Center in Boston led to new methods for 1) accelerated dynamic MR imaging using linear and non-linear machine learning-based image reconstruction (PhD of Y. Djebra [384, 385, 425]), and 2) improved brain PET quantification using super-resolution and non-negative matrix factorization (PhD by Y. Chemli [365, 364, 366]). New deep learning methods have also been designed for 3-dimensional reconstruction for breast tomosynthesis, including uncertainty estimation (PhD by A. Quillent [452], with General Electric).

Furthermore, we also launched new collaborations on AI for new segmentation application domains, such as histopathology images (PhD by A. Pirovano with KeenEyes [448, 449, 451, 450], PhD by A. Mammadov with St Joseph hospital, PhD by A. Habis with Institut Pasteur [401] and MSc project by S. Naik with Imperial College London [440]), OCT [403] and spine modeling (PhD by S. Ebrahimi with Arts et Metiers ParisTech [390, 393, 389, 390]). We pursued our activity in biological imaging with compressed-sensing methods applied to fluorescence microscopy denoising (PhD of W. Meiniel with Institut Pasteur [427]) and OCT acquisitions (PhD of W. Meiniel with Columbia University [419]). We continued our collaboration with Columbia University on very large cohorts of lung images to phenotype emphysema using machine learning [353, 474]. Finally, we initiated a number of collaborative projects on novel biological image computing challenges such as neuron tracking on fluorescence imaging of live animals (PhD of R. Reme with Institut Pasteur [349]), or factorial decompositions of uncalibrated bioluminescence images (PhD of E. Dereure with Institut Pasteur [383]). These two recent initiatives led to new collaborations within faculty members of the IMAGES team.

Remote Sensing Activities in remote sensing have been mainly devoted to SAR (Synthetic Aperture Radar) imaging and also from 2021 onwards to hyperspectral imaging. For SAR imaging, three main topics have been investigated: speckle reduction, segmentation and classification, and 3D reconstruction.

Major developments have been proposed for speckle reduction using deep learning frameworks and exploiting the physics of SAR acquisition systems or the multi-temporal potential of satellite sensors (PhD by E. Dalsasso [377, 376], PhD by I. Meraoumia [428], ASTRAL project -ANR ASTRID). Supervised and self-supervised methods exploiting temporal diversity or the complex nature of the data have been proposed. The proposed frameworks have been extended to polarimetric data, interferometric data and multi-sensor inputs. The obtained results are state of the art for speckle reduction and have been acknowledged by two awards (best paper of IGARSS 2021 [378] and 2nd best student paper of EUSAR 2022 [375]).

Concerning segmentation and classification, the team was involved in the preparation of the SWOT mission (NASA/CNES satellite) as part of the Algorithm Definition Team and also developed classification methods for lakes and rivers based on linear structure detection and Markovian modeling (PhD by N. Gasnier [442], in collaboration with CNES). Edge detection with a contrario and deep learning methods adapted to SAR statistics has also been proposed (PhD of C. Liu [420]). As for 3D reconstruction, a major effort has been made with regard to SAR tomography as part of the ALYS project and the PhD by C. Rambour for the reconstruction of urban areas using spatial regularization and specific graph-cut based optimization [453, 454, 453]. For forest applications and in preparation for the BIOMASS mission (ESA satellite), new deep learning based reconstruction methods are being developed (ongoing PhD by Z. Bérenger [356]). Both supervised approaches and self-supervised learning through equivariant imaging have been proposed. Multi-view reconstruction based on radiometric information is also currently studied through NERFs approaches.

We also worked on a related topic in a CIFRE PhD with Valeo on deep learning for radar data exploitation of autonomous vehicles (PhD of A. Ouaknine [444, 445]).

Concerning hyperspectral imaging, deep unrolling methods have been explored to propose new interpretable hyperspectral unmixing methods. In this context, auto-supervised training strategies have been considered by simulating the required training sets automatically from the considered data (ongoing PhD by R. Hadjeres).

The topic of multi-temporal analysis of remote sensing images and change detection has been investigated both for optical data (PhD by R. Daudt with the release of datasets for change detection benchmarks and the development of weakly supervised methods and robust to domain shift [379, 380]) and SAR images (PhD of W. Zhao [479]). Work on cloud detection with texture synthesis based on physically constrained generative networks has also been developed [362].

The SAR activities are supported by ANR ASTRID projects (ALYS 2016-2020, ASTRAL 2022-2026), CNES fundings, Futur and Rupture Fondation Mines-Télécom fundings, AID funding and CSC (Chinese Scientific Council) PhD funding. Collaborations are led with national partners (IETR Université de Rennes, CNAM, MAP5, CESBIO, ONERA) and international academic partners (Tromso University Norway through COSMIC project, Universität der Bundeswehr München through Bay-France project). In addition to publications, the developed methods are accessible as open-source code on the RING (Radar Imaging Group) gitlab <https://gitlab.telecom-paris.fr/ring/>.

Computer Graphics The team has been making notable contributions to 3D and even 4D data manipulations while addressing a wide variety of research and development problems for efficient and effective digital content creation. In rendering, which is a crucial topic in digital image synthesis, a novel material morphing method that preserves details of two material textures has been proposed [395] and a multi-scale rendering technique for dense dynamic stackings such as sand [432] has been developed.

In image synthesis, having the necessary means to model and manipulate 3D geometry is essential. To this end, a high-quality implicit surface reconstruction algorithm [478], a spectral-preserving

mesh simplification [418], a free-form deformation method using cages [464, 369], and a parametric shape manipulation method using direct acyclic graph [433] have been proposed.

In creating computer animation, which involves one additional degree of freedom (i.e. time) on top of the spatial dimensions, the team has focused on the physics-based simulation approach. In particular, stable, energy-preserving, efficient simulation methods for soft bodies and fluids have been developed [405, 417, 404].

A unique specialty of computer graphics is its connection to the arts. The team has demonstrated its expertise in a sketch-driven approach. Instead of relying on 3D representation, artistic manipulation of 2D images and geometries has been developed [446, 426, 443].

Moreover, thanks to the team's expertise in both computer graphics and machine learning, the team has been carrying out research into applying machine learning techniques to computer graphics problems. This includes, among others, texture mapping [394] and physics-based simulations [465, 538], which result in superior methods to the traditional ones.

Image processing/Computer vision The last orientation of our team's research activities is focused on natural images and includes works at the interface between image processing, computer vision and computational photography. Since the beginning of the period covered by this report, our activity has mainly shifted toward deep learning approaches, with a strong interest in generative models.

A first recurrent area of interest lies in the understanding and structuring of latent spaces of generative models. In [441], we have investigated in detail the inner working of simple architectures dedicated to elementary geometric shapes, shedding some light on the way networks handle geometric attributes. In [447], a generic method for structuring the latent space of autoencoders is proposed, taking inspiration from PCA decompositions. Our team also took interest in the structuring of latent spaces for the specific task of face synthesis and editing. Methods have been proposed for face aging [477], for computing spatially varying editing direction in the latent spaces of StyleGan-like architectures [475] or building intrinsically disentangled latent spaces [347] and for the editing of videos of animated faces [476].

Another important activity field for our team is texture modeling and synthesis. Here too the main framework is deep generative models. We have significantly improved the state-of-the-art optimization-based approaches to texture synthesis through the careful development of spectral losses and multi-scale schemes [397]. In partnership with Onera, we have developed synthesis methods dedicated to cloud field synthesis and super-resolution, both for visual images and for images of physical properties such as ice or water content [362]. These works build on classical GAN (Generative Adversarial Networks) that are revisited to take into account fractal properties of cloud fields as well as other specific statistical constraints. We have also developed a generic method for the universal synthesis of visual textures, leveraging an autoencoder with self-similar properties and the ability to control long range statistics [363].

Significant effort has also been devoted to learning strategies for deep architectures. In the field of cultural heritage analysis, we have developed semi-supervised methods for iconographic element detection [398, 399], adapted to databases that are only lightly annotated. In the same field, we have also investigated transfer learning approaches for painting classification tasks [396]. More recently, we have developed a fully synthetic learning strategy for image restoration tasks, where databases of natural images are entirely replaced by synthetic images, with geometric [350] as well as color [348] priors. To the best of our knowledge, this work is the first to show the feasibility of using synthetic training for real-world restoration tasks [351].

The team also has a long term expertise in patch-based image and video synthesis/inpainting methods [416]. Recently, this expertise has evolved toward internal learning-based methods, including efficient attention mechanisms inherited from patch-based algorithms [368] and single-image diffusion models for image and video inpainting [367]. To the best of our knowledge, our models are the first diffusion models making it possible to inpaint and synthesize complex videos.

Our work on the automatic assessment of the aesthetic qualities of photographs [424] led us to develop an inventory of the current state of research in this field and to show that, if techniques

based on deep networks currently allow a suitable evaluation of objective aesthetic properties, no operational method as yet (based on recommendation methods, social networking or online tests) allows an evaluation of the specific subjective qualities for a given observer.

15.3.2 Potential and dissemination strategy

The team has a sustained publication activity in all its methodological and applicative components, with publication strategies that vary depending on the scientific community, alongside a varying emphasis on conferences or journal publications. Exchanges between team members are regular (weekly team meetings and casual exchanges) and facilitate collaborations between junior and senior members. This, together with a progressive teaching load, enables junior members to maintain regular and high-quality publishing records.

15.3.3 Scientific integrity, ethics and open science

The team is highly concerned with reproducible research and a large proportion of published works have publicly available codes. The team also participates in the IPOL Journal, whose aim is to promote reproducible research. Several datasets have been collected by the team, in particular for SAR imaging, change detection, automatic painting analysis and autonomous driving (CARRADA, in partnership with Valeo).

Following government instructions, IMT has appointed Henri Maître as the RIS-IMT (Scientific Integrity Officer) for its schools. As such, it has set up a network of RIS-delegates (one per school) working in narrow relationship. In addition to appraising cases of alleged misconduct, this network has maintained an important training function (both for PhD students and researchers), resulting in courses and conferences. Henri Maître also participates in the CoER (Research Ethics Committee) of IPP, as well as the IMT Open Science Group.

15.3.4 Synthetic self-evaluation

Strengths The team's scientific production spans a wide thematic range, is balanced between applications and methodological contributions, and includes publications in high quality journals and conferences, usually accessible as preprints, publically accessible codes and databases as well as integrations of the outcomes of industrial and societal collaborations.

Weaknesses As with every team, scientific work was affected to some extent by the pandemic, although no significant impact on production has been noticed. The team also publishes and disseminates its work in several different communities, that may affect its visibility as a single entity.

Opportunities The team's research themes are particularly up to date, as already mentioned. Its activity benefits from an original positioning at the intersection between deep learning approaches and expertise in image modeling and applied mathematics.

Threat The scientific production of the team is partly dependent on computing facilities and this dependency should be kept under control. There is also a risk that the numerous industrial projects, in particular CIFRE theses, might have too great an impact on the research themes considered.

15.4 Contribution of Research Activities to Society

15.4.1 Socioeconomic partnerships and interactions

The medical imaging activities of the team are developed in partnership with an extensive number of practitioners and hospitals (Bicêtre, Necker Enfants Malades, Sainte-Anne, Pitié-Salpêtrière,

Lariboisière, Robert Debré, XV-XX, Cochin, HEGP).

The team has a longstanding collaboration with CNES on subjects related to environmental issues. Some members were part of the Algorithm Definition Team (ADT) for SWOT NASA/CNES mission on water surface cartography. They are currently collaborating with CESBIO in link with the coming BIOMASS mission.

Ex-students from the internal training organized by the team (IMA track at Télécom Paris), the MVA master or PhD students are active at all levels of the imaging industry, from start-ups to large groups. The team is directly involved in the organization of the MVA master (co-direction), which hosts around 250 excellent students per year and is arguably the first source of recruitment for company implied in artificial intelligence activity in a wide sense. As an example, one of the founder of the French company Mistral attended both the internal training and the MVA master. The team has many industrial partnerships, mostly as CIFRE theses (Valeo, Kanop, Interdigital, Incepto, Guerbet, General Electric, Philips, L'Oréal, Skairos, etc.), but also as bilateral collaborations and sponsorship. The team also regularly participates in continuing education.

15.4.2 Research valorization and transfer

The team is involved in valorization activity and transfer. It has conducted four IP Paris pre-maturation projects. It has two patents on medical imaging [382, 466] (with Guerbet and Necker hospital), a US patent on multi-image restoration [400], filed exclusively by members of the team, and an APP code deposit on medical imaging. In the field of computer graphics, several codes have been transferred to industry (Praxinos and GeometryFactory).

15.4.3 Science popularization

Team members have participated in presentations for the general public, in particular for a young audience (Maths en Jeans, Maison Poincaré, Cité des Sciences, various schools, visiting day for highschool girls, etc.). Popularization papers have been written for Polytechnique Insights, Telecom journal, the Ethics Committee of SFR (French Radiology Society) and Images des Mathématiques.

15.4.4 Synthetic self-evaluation

Strengths The fields of application of the team's work are intrinsically related to societal concerns: biomedical imaging, remote sensing imaging, wide audience imaging and entertainment. These activities take the form of a wide range of collaborations with medical practitioners, hospitals, space agencies and industrial partners. They have a direct effect on fundamental issues such as public health or environmental monitoring.

Weaknesses Research valorization activities are relatively limited and could be developed.

Opportunities The aforementioned areas of activity have witnessed a significant increase in real use cases in recent years, such as in medical imaging, where automated diagnostic aids are becoming more prevalent, in remote sensing imaging, with the launch of many acquisition campaigns, or with the increased importance of computational photography algorithms in smartphones.

Threats Industrial projects and requests are many, in particular for CIFRE theses, and we are vigilant to ensure that these activities are not carried out to the detriment of our methodological contributions.

Chapter 16

Self-assessment of MM team

16.1 Profile, Resources and Organization

16.1.1 Scientific objectives

The research of the Multimedia (MM) team encompasses the entire life cycle of multimedia documents and signals, including acquisition, coding, transmission, transport, interactivity, analysis, and generation. Our work is primarily concentrated on two key areas: *transmission of multimedia data*, and *efficient deep learning for visual and multimodal data*.

In the field of **efficient multimedia data transmission**, our team has demonstrated significant expertise in image and video compression, including both traditional and deep learning approaches. We have also made notable contributions to robust video transmission, with a substantial body of work in distributed video coding, network coding, and linear video coding. Additionally, our research includes interactive and adaptive multimedia streaming for next-generation protocols, showing our commitment to innovative streaming technologies: this is particularly reflected by an ever-growing academic and industrial community around our GPAC platform.

Recently, our focus has expanded to include research on **efficient deep learning for visual and multimodal data**, predominantly in the analysis of visual data, such as images and videos, while also addressing challenges involving textual data. Our methodologies emphasize the development of techniques for learning with limited examples or computing resources.

The MM team is dedicated to producing research that is both methodologically sound and practically applicable in these fields. This objective is pursued through extensive collaborations with both academic partners, including the Universities of Trento (Italy), Genova (Italy), Aberdeen (UK), Torino (Italy), Naples Parthenope (Italy), Delaware (USA), MPI (Germany), École Polytechnique, Inria, CentraleSupélec, and Insa, as well as industrial partners such as Meta, Atos, DXOmark, Canon, Ateame, Netflix, Enensys/Teamcast, Streamroot, among others.

Following its relocation to the Saclay plateau, the MM team has benefited from the research environment fostered by IP Paris. We actively contribute to the scientific objectives of the interdisciplinary AI center, Hi! PARIS, and enjoy the benefits of its funding, which supports a faculty member, a post-doc, and a PhD grant. The team also leverages initiatives from IP Paris, such as the PhD tracks, and from Université Paris-Saclay, particularly through the Labex DigiCosme program. Our active participation extends to teaching, with significant involvement in various courses. We contribute to the master's programs at IP Paris, including Data Science and Data AI, and participate in the Multimedia Networking master's program in conjunction with Paris Saclay.

16.1.2 Resources

Team leader: Stéphane Lathuilière.

Faculty: Stéphane Lathuilière (Associate Professor, October 2019-present), Jean Claude Dufourd (Research Director), Marco Cagnazzo (Associate Professor, October 2018, Full Professor Novem-

ber 2018-December 2021), Attilio Fiandrotti (Associate Professor, April 2018-May 2020), Jhony Giraldo, (Associate Professor, October 2022-present), Jean Le Feuvre (Associate Professor, October 2018, Research Director, December 2023-present), Jean-Claude Moissinac (Associate Professor), Enzo Tartaglione, (Associate Professor, October 2021).

Associate Professors: Attilio Fiandrotti (LTCI associate researcher 03/2023-), Marco Cagnazzo (LTCI associate researcher 01/2022-).

Non-permanent human resources: PhD students, post-docs, engineers

Non-permanent staff 2018-2023				
Year	PhD students	Post-docs/Engineers	Invited	Total
2018	11	4	1	16
2019	10	5	1	16
2020	8	5	1	14
2021	8	4	2	14
2022	9	3	1	13
2023	7	6	4	17

Equipment - Computing Facilities. The scientific activities of the team are demanding in terms of GPU computing. The team uses pooled resources, at the local and national levels (LTCI/IDS cluster, Jean Zay). This is complemented by 20 GPUs purchased by the team using specific project funding. These GPUs are shared with the entire laboratory in a preemptable mode, managed through a resource allocator. More details are provided in Sec. 16.2.4.

Funding. Despite the absence of regular funding, the team ensures its financial stability by diversifying its sources. This includes participation in public calls for projects, CIFRE PhD programs, bilateral contracts, and sponsorships. The team also contributed to the industrial chair DSAIDIS in the period 2019-2023.

2018-2023 (K€)							
	2018	2019	2020	2021	2022	2023	Total
Public National	343	188	26	62	96	220	934
International	59						59
Partnership & Transfer	108	177	120	224	262	376	1,266
Total	510	365	145	285	358	596	2,259

TABLE 16.1: MM financial resources.

16.1.3 Human resources management, safety, environment, ethical protocols, data and scientific heritage protection

To maintain the optimal functioning of the team, various meetings are regularly scheduled at the team level. In practical terms, a weekly time slot is reserved, and its utilization varies based on current needs. This time can be allocated for a team meeting to address practical issues, a scientific reading group, a seminar featuring external speakers, or an annual welcome day for new members.

In terms of gender equality, we face a significant imbalance, as none of the permanent members are women. We were extremely vigilant about gender equality in our last recruitment process, but unfortunately, we did not receive sufficiently strong applications from women during the recent recruitment campaigns. This disparity is much less pronounced among non-permanent members, where we have a more balanced representation with several female post-docs and PhD students. However, our team has an exceptionally high level of cultural diversity, with permanent and

non-permanent members representing over ten different nationalities. This diversity ensures an enriching and mindful working atmosphere.

The environmental footprint of our team primarily results from two factors: travel to conferences and GPU computing. Regarding travel to conferences, the high prestige of conferences in our field often necessitates extensive travel. To mitigate this, we have implemented several strategies: i) We focus on publishing fewer papers at top-tier conferences rather than numerous papers at less selective ones. ii) We prioritize attending conferences within Europe whenever feasible. iii) Typically, only the PhD student associated with the work attends the conference. iv) Some team members have adopted a personal policy of limiting themselves to one flight per year for conference attendance. The impact of GPU usage is twofold: electricity consumption and hardware demands. To minimize these impacts, we have coordinated our computational resources at the laboratory level. This organization: i) Allows us to utilize machines with more efficient cooling systems. ii) Enables the use of a batch scheduler to maximize machine usage and efficiency. iii) Helps extend the average lifespan of our hardware by optimizing utilization and maintenance.

16.1.4 Synthetic self-assessment

Strengths: The significant evolution in the research areas of the MM team demonstrates our successful adaptation to the methodological shift triggered by deep learning. This has profoundly influenced multimedia research and our rapid evolution has attracted young and highly productive researchers. Recent recruitment efforts have proven highly beneficial, as evidenced by securing record levels of funding and achieving the highest total count of non-personal staff in 2023. Despite this shift, the team still excels in bridging industrial and academic research, consistently aligning with top international standards. This is evidenced by our many publications at major conferences and numerous industrial partnerships (see 16.2.1 and 16.4.1).

Weaknesses: Recent departures of senior personnel, especially Marco Cagnazzo, have somewhat weakened the team. Additionally, the team’s broad scope of activities appears challenging to manage given its relatively small size.

Opportunities: The advent of advanced multimodal language models, such as GPT-4, has reinvigorated interest in multimodal learning. This development is likely to enhance the scientific impact of the team’s research, offering new avenues for exploration and contribution. The urgency of reducing the human carbon footprint is also impacting the content delivery world, and part of the team’s activity is now focusing on optimizing existing protocols and production chains using our expertise on multimedia adaptation and transport.

Threats: There is a noticeable decline in the team’s focus on research in compression technologies. Special attention is required to both preserve and continue developing this area of world-class expertise, ensuring that this crucial aspect of the team’s research portfolio does not diminish. To this aim, we have focused our research on new hybrid and end-to-end compression approaches [539, 512, 514, 512, 513]. Furthermore, MM’s relatively small size means that any departure could pose a risk to its stability and scientific coherence.

16.2 Attractiveness

16.2.1 Scientific reputation and contributions

The team is highly recognized both nationally and internationally. Its members actively contribute to the academic community, serving on editorial boards of premier multimedia journals (IEEE TMM, IEEE OJCSVT, IEEE TCSSVT). They also participate in the program committees of leading conferences in the field, including but not limited to CVPR, ICCV, ECCV, NeurIPS, ICLR, AAAI, AISTATS, ICASSP, WACV, and ICIP.

The scientific reputation of the team is further bolstered by regular publications in A*-ranked conferences (17 publications at CVPR, ECCV, ICCV, ICLR, and NeurIPS) or top journals (2 T-PAMIs). The publication strategy of our team aligns with the prevailing trend in our specific

research communities, where top-tier conferences are often regarded as more prestigious than most journals. Furthermore, they have played significant roles in organizing or presenting at numerous influential conferences and workshops (Open-source competition at ACM Multimedia 2022, Deep Learning Indaba 2023, Tutorial sessions at ICIAP 2019/2021, Special Session at IEEE ICIP 2022, Special Session "GraDSci: Graph Data Science and Applications" at IEEE DSAA 2023, workshop on compression and frugality for AI at ECML-PKDD 2023, workshop LatinX in CV Research at ICCV 2023, and workshop LatinX in CV Research at CVPR 2023). The team has also actively contributed to ISO/IEC JTC1/SC29 (MPEG) and has been the editor of several MPEG standards since 2018. The team's excellence is further highlighted by the awards received during the recent period (Emmy Technical Awards in 2021 and 2022, Eduardo Caianiello's best paper award in 2023 for [541], the best paper award for the artificial social intelligence workshop at ICCV 2023 for [489]).

16.2.2 Staff hosting policy

For faculty members, the laboratory-wide policy of reduced teaching loads facilitates their smooth integration into the team. Additionally, co-supervision of PhD students is instrumental in accelerating their autonomy within the Multimedia (MM) team. A telling sign of our commitment to integrating recruits is the number of PhD co-supervisions that young associate professors take on shortly after joining. For instance, Jhony Giraldo, who has been with the team for only one year, is already involved in supervising 4 PhD students and 1 post-doc, exemplifying this supportive and collaborative environment.

The recruitment of PhD students by our team is characterized by a diverse range of academic backgrounds and a high caliber of candidates. This can be partly attributed to the team's strong commitment to teaching in various master's programs, such as Data Science, Sata AI, and Multimedia Networking. Additionally, our involvement in the PhD track program of IP Paris plays a significant role in attracting a variety of quality applicants to our team.

A distinctive feature of our team is its remarkable international diversity, with multiple nationalities represented among both faculty members and PhD students (9 different nationalities at the moment). This multicultural composition fosters a conducive environment that is beneficial scientifically by enriching the team's dynamics and perspectives. Our team's international appeal is bolstered by the diverse group of visiting PhD students we've welcomed from different institutions and countries, including the University of Torino (Italy), the University of Granada (Spain), and the Sapienza University of Rome (Italy).

16.2.3 Success in competitive calls for projects

The team successfully secures funding for its various internships, PhD students, post-docs, engineers, computation equipment, and operating expenses through a range of competitive project calls. Our diverse funding sources encompass:

- ANR Projects: ANR ZL-LVC (AAPG 2020 / CE25, PI M. Cagnazzo) on zero-latency linear video coding; ANR JCJC Odace (AAPG 2020 / CE23, PI S. Lathuilière) on online domain adaptation in changing environments; ANR SODA (TSIA 2023 / Team Members E. Tartaglione and J. Giraldo) system on chip design leveraging artificial intelligence.
- FUI and related programs: FUI23 "ConvergenceTV" (17-19) on next-generation broadcasting protocols, iDemo "Smart-CD" (23-26) on greener infrastructures for multimedia distribution
- Participation in the Industrial chair Data Science and AI for Digitized Industry and Services, in charge of the second research area: *Exploiting Large Scale, Heterogeneous, Partially Labeled Data*, [webpage](#)
- PhD grants and post-doc fellowship from Hi! PARIS, PhD track from IP Paris, Labex DigiCosme
- The CIFRE PhD program collaborates with industry leaders on various innovative projects:

- **Meta:** Generative image models for complex scenes and latent representation inference.
- **Atos:** Unsupervised domain adaptation for person re-identification.
- **DXOmark:** Automatic image quality analysis via neural networks.
- **Zodiac:** Compression techniques for airplane cockpit videos.
- **StreamRoot:** Adaptive streaming in hybrid broadband/peer-to-peer networks.
- **Orange:** Compression of multi-view content for immersive video coding (2 projects).

16.2.4 Equipment quality and technological skills

The primary equipment requirements for MM revolve around computational power, particularly GPUs for deep learning research. Our in-house computing resources are managed at the scale of the laboratory. It comprises approximately 150 GPUs, managed with a Slurm resource allocator. These GPUs, including P100, V100, A100, and L40s models, are distributed across 50 nodes. For storage solutions, we have 200TB of high-performance storage, able to deliver 150Gb/s of bandwidth, and a slower space of 400TB for long-term storage. This setup is augmented by 5 additional computation nodes equipped with smaller gaming GPUs (e.g. RTX 3090). Furthermore, we have access to an OpenStack Cloud Computing platform, which supports the creation of up to 500 virtual machines. These facilities are primarily used for prototyping and are supplemented by access to national clusters such as Jean Zay or internal private clusters for CIFRE PhD students. Additionally, the team is equipped with multiple high-quality monitors and specific lighting spots for conducting in-house controlled user evaluation experiments.

16.2.5 Synthetic self-assessment

Strengths: The team’s academic excellence has earned it high international visibility. Its unique positioning at the intersection of traditional transmission research and deep learning in multi-media research enhances its attractiveness. Located at the forefront of booming methodological areas, it benefits from a rich ecosystem and available networks, steadily bolstering its integration capabilities.

Weaknesses: The absence of a senior researcher or professor impacts the team’s influence and its ability to participate in organizing major scientific events.

Opportunities: The team’s international acclaim, coupled with its increasing involvement in various master’s programs, is likely to aid in attracting top students for PhD programs.

Threats: Straddling the line between upstream and technological research, the team faces competition from both academic and industrial sectors, potentially challenging its long-term viability. Companies operating in similar fields offer higher salaries and relative research freedom compared to most research areas, along with substantial computational resources, which could pose a threat to retaining and attracting talent. Moreover, our research heavily depends on the Jean Zay national cluster. The challenge of accessing resources from this cluster often becomes problematic as we approach deadlines. Furthermore, access restrictions for certain nationalities significantly impact our research and our ability to attract international talent. Security checks can take several months, and acceptance notifications are generally only received after the commencement of PhD projects. This may lead to situations where we discover, post-initiation of the PhD, that we must alter the project scope due to access to Jean Zay being denied. Although this scenario has not yet occurred within our team, its potential impact has already compromised our attractiveness, leading to instances where foreign candidates have declined to join our team for this reason.

16.3 Scientific Production

16.3.1 Qualitative analysis

The scientific output of the MM team is related to two principal areas. Firstly, the majority of the production is focused on scientific publications at international conferences and in journals. In par-

Publications 2018-2023 (source HAL)				
Year	Total	Journal	Proceedings	Chapters/Reports
2018	20	3	17	0
2019	19	8	11	2
2020	11	1	10	1
2021	21	5	16	0
2022	17	3	14	1
2023	34	3	31	3

TABLE 16.2: Scientific output of the MM team.

ticular, the team mostly targets A*-ranked conferences (17 publications at CVPR, ECCV, ICCV, ICLR, and NeurIPS) or top journals (2 T-PAMIs). Our publication strategy is in line with the dominant trends within our research communities, where top conferences are often held in equal or higher esteem than journals. Secondly, the team is actively engaged in patenting and standardization efforts, contributing to 7 standardization proposals, participating in the establishment of 12 international standards, and securing 26 patents or patent extensions.

Topic - Transmission of multimedia data

Contributors: Marco Cagnazzo, Attilio Fiandrotti, Jean Le Feuvre, Stéphane Lathuilière, Enzo Tartaglione

In this topic, we have made numerous contributions focusing on video coding and processing to enhance the efficiency of transmission. The first set of contributions in this area, primarily supervised by Marco Cagnazzo, revolves around Linear Video Coding (LVC), a paradigm for efficient video transmission to multiple users [571, 570, 569, 570, 557, 558]. LVC might suffer from relatively high transmission latency, and thus controlling latency in LVC and video transmission systems, in general, is an important area of research which is the subject of the ANR-funded "Zero-latency Linear Video Coding Project" (AAPG 2020 / CE25) [510, 562, 564, 563]. For this project, Marco Cagnazzo is the PI of a four-member partnership. Another research area is hologram progressive transmission [498, 544, 499, 497, 545]. Several aspects of immersive media have been also studied: compression, transmission, and view synthesis, in particular in the context of MPEG standardization [509, 537, 535, 536, 508, 525, 524, 523, 502]. The compression of special types of video has also been studied in various publications. For example, the particular case of airplane cockpit videos has been addressed in [530, 529]. Another example is our development of specialized codecs for video conferencing, which are based on deep image animation techniques [512, 513, 512, 514] with funding from DigiCosme. A more recent area of research is related to the watermarking of neural networks for multimedia applications [570, 491] with funding from DigiCosme – Initiative Transverse scheme [570]. Other research areas investigated include Adaptive video streaming [511], Neural-network image compression [561, 565], and video delivery over lossy packet networks [511, 535].

Another key research area, mostly supervised by Jean Le Feuvre, is the development of adaptive HTTP streaming within Peer-to-Peer architectures, leveraging machine learning to optimize client decision-making. This line of research is presented in the first item in our portfolio. Our contributions also extend to next-generation broadcast distribution, GPAC architecture for future multimedia technologies, and the MPEG standard for uncompressed video and images in ISO/BMFF, including work with multi-band and hyperspectral images. Jean Le Feuvre is also involved in the optimization of the ISO Base Media File Format in partnership with Canon Research France, and supporting the industry with GPAC deployment in production setups, especially Netflix. In 2022, he initiated a project on eco-responsible multimedia, granted in 2023. His output includes one journal article, nine conference articles, 87 standardization contributions resulting

in 44 documents and 12 international standards, and 26 patents or extensions. He has received several awards, including the NAB Innovation Award in 2018 for the Convergence TV project, an Emmy Technical Award in 2021 for the ISO Base Media File Format, and another Emmy Technical Award in 2022 for the Standardization of HTTP Encapsulated Protocols.

Topic - Efficient learning for visual and multimodal data

Contributors: Enzo Tartaglione, Attilio Fiandrotti, Stéphane Lathuilière, Jhony Giraldo, Jean-Claude Moissinac

The research in this topic is organized around four areas: *Deep generative models*, *Learning with limited or imperfect supervision*, *Efficient deep learning* and *Multimodal graph-based learning*. Across all these research areas, we have recently begun exploring the use of textual information in visual recognition or generation systems. Our research into image and video synthesis, mostly supervised by Stéphane Lathuilière, has focused on reducing data and supervision needs without compromising on the quality of the output [509, 548, 490, 487, 506, 486, 520, 480, 534, 521, 519, 515, 548, 549]. His work shows that effective synthesis can be achieved with less reliance on extensive annotations or detailed task-specific models. A significant part of this research is performed in the context of a CIFRE PhD project with Meta. This line of research is presented in the third item of our portfolio. A strictly related problem is the generation of virtual views for multi-camera video content, which has been addressed in [509, 560, 536]. Attilio Fiandrotti has also been involved in this line of research through the BHAIR ANR-21-CE38-0001 project that focuses on the detection of graphical objects in medieval artifacts.

Regarding the second research area, our work focuses on deep learning across different data availability constraints (missing or imperfect supervision) [566, 517, 736, 559, 567, 543, 546, 501, 560, 492, 507, 493, 547, 500, 568, 509]. These research initiatives are mostly performed as part of ANR-JCJC and CIFRE PhD scholarships with Atos and Dxomark, and academic collaborations with the University of Trento (Italy). Among these various settings, we have emphasized unsupervised domain adaptation where the goal is to improve the performance of models in new, unlabeled domains, with specific applications in semantic segmentation, person re-identification, and 3D object detection. Attilio Fiandrotti has also made multiple contributions in this field focusing on image processing using deep neural networks [522, 484]. Enzo Tartaglione's research in this area is dedicated to representation learning focusing on removing spurious features from learning tasks, specifically targeting debiasing in these studies [481, 551, 482, 554]. This line of research is presented in the second item in our portfolio.

The third area, mostly supervised by Enzo Tartaglione, focuses on making learning and usage of deep neural networks efficient. Efficiency in such a context has been mostly explored in both directions of reducing the model's complexity through pruning and by reducing computation at training time [556, 553, 556, 831, 550]. Recently, these algorithms have been challenged by the emergence of the sparse double descent phenomenon: over-parametrized deep models do not necessarily obey the classical bias-variance trade-off, as the size of the model acts as an implicit regularizer. This challenges pruning approaches based on early-stop rules, and research to address this problem is currently being conducted [860, 541]. In terms of applications, Neural Radiance Fields have recently revolutionized rendering applications. Around this subject, work has been conducted, to reduce the model's size [494], to reduce data payload [525], and to further boost neural radiance field performance employing ensembling [495]. This work is concurrent with pruning: indeed, some computations can be "pruned" at training time, towards energy and computation saving [552, 485] and even grouped convolutions can be pictured as an efficient way of ensembling [516]. Attilio Fiandrotti has also made significant contributions in this area with research into the deployment of deep neural networks on mobile or resource-constrained devices [550, 555]. Enzo Tartaglione is also supporting the IP Paris European Project "ELIAS" (grant n.101120237) in the research initiative "Reducing the energy requirements of computation".

The final research area focusing on graphs is mostly supervised by Jean-Claude Moissinac and Jhony Giraldo. Our research has addressed fundamental questions in graph neural networks

related to over-smoothing, over-squashing [505], sparsity, and scalability [504]. Besides these fundamental studies, we have applied graph-based techniques in multiple applications such as image segmentation [503], video processing [540], social computing [489], and time-series analysis [488]. We have also undertaken work to evaluate different methods for combining knowledge semantic representation (RDF) approaches and entity vector representation approaches [527]. An original feature of this work is the treatment of sub-graphs of large knowledge graphs, referred to as Context Graphs [526, 528]. This work is now focusing on the results that can be expected from semantic methods based on knowledge graphs, combined with the latest machine learning methods. We have mainly been working on datasets describing French cultural heritage entities. To this end, datasets have been produced and published [532, 531].

16.3.2 Potential and dissemination strategy

The internal dissemination of knowledge within our team is structured as follows. Firstly, we hold a weekly team meeting attended by all members, including both students and academics, to share and discuss recent work. Secondly, every team member, particularly PhD students, actively engages in scientific presentations at various levels, including the department, the lab, the school, or IP Paris, to disseminate our research findings.

Concerning variability in our scientific production, a few observations can be made. The lower amount of publications by certain team members can often be attributed to their significant involvement in teaching, administration, or other tasks. Moreover, our team’s publication patterns align with trends observed within our scientific communities: researchers in computer vision generally produce more papers than those in traditional multimedia processing. Computer vision researchers also tend to prefer conference publications, while those in signal processing often target journals. Additionally, our researchers in compression and multimedia communication systems focus not only on scientific publications but also on patenting and standardization activities.

Finally, we can observe that the junior researchers recently hired have prolific publication activities. It shows the success of Télécom Paris’s practice consisting of reducing the teaching load for new assistant/associate professors.

16.3.3 Scientific integrity, ethics and open science

Our commitment to open research is multifaceted and robust. We ensure that all our publications are accessible on HAL, and most are also available on arXiv to enhance dissemination. In pursuit of reproducibility, we have released the source code for most of our projects under an open-source license. In many projects, we also release Jupyter notebooks that can be run on Collab to facilitate the use of our code and fast prototyping by other researchers. Also of note are the team’s efforts in the open GPAC multimedia platform. Our dedication to open-source is further exemplified by S. Lathuilière’s role as an organizer of the open-source competition at ACM Multimedia 2022. Furthermore, our works are predominantly published at renowned conferences such as CVPR, ICCV, NeurIPS, and ICLR, which provide open access to their proceedings.

Regarding ethics, our team has implemented several measures. Firstly, we engage in public awareness campaigns concerning the implications of generative AI, especially the risks posed by deep fakes. More details on these initiatives can be found in Sec. 16.4.3. Secondly, our scientific research often involves experiments with human-related data. We proceed with the utmost care in these situations. Particularly in the fields of generation and compression, human evaluations are frequently employed to gauge human preferences. In such instances, we collect no personal data beyond visual preferences.

16.3.4 Synthetic self-assessment

Strengths: A key strength of the team is its remarkable publication record. Additionally, the team’s scientific positioning is quite distinctive, situated at the intersection of multimedia transmission, efficient learning, multimodal analysis, and generation, with a particular focus on vision.

The involvement of Stéphane Lathuilière in the IDS/LTCI cluster allows the team — and the entire laboratory — to benefit from a high-performing GPU cluster with the support of local research engineers, further enhancing our research capabilities. The open-source GPAC project is gaining more and more traction from the industrial and academic worlds, reflecting the team's strong beliefs in open and reproducible research.

Weaknesses: The diversity of our scientific background is one of our main strengths but it comes with a weakness. By contributing to various communities, it makes it harder to maintain high visibility in a single community and be clearly identified.

Opportunities: The team is working on booming topics such as deep learning for multimodal data and efficient deep learning.

Threats: Turnover is high. This can be mostly explained by the numerous opportunities in our research area both in academia and the industry. The research area requires large-scale computing facilities. Our research strongly relies on the national cluster Jean Zay as discussed in Sec. 16.2.5. This strong dependence is not only a threat to our attractiveness but also to our capability to sustain the production of top-quality scientific work.

16.4 Contribution of Research Activities to Society

16.4.1 Socioeconomic partnerships and interactions

The team maintains numerous activities in the form of socioeconomic partnerships with the non-academic world. Firstly, as detailed earlier, an important part of our research activities is conducted with industrial partners (primarily through sponsorship, bilateral contracts, and CIFRE PhD theses). Secondly, our team plays a significant role in continuing education programs, overseeing two courses: "Video Compression and MPEG Standards" and "Broadcasting Techniques." We have noticed a decline in demand, leading to the decision in 2020 to offer these programs solely upon request. However, they continue to be conducted, on average, once a year. Notable companies such as Nokia and Intel have benefited from these courses. To counterbalance the waning interest in these specific courses since 2020, we have engaged in the "Certificat d'Études Spécialisées (CES) in Artificial Intelligence" offered by Télécom Paris and ENSTA. Our involvement in the DSAIDIS chair also fosters a conducive environment for future collaborations (e.g. ANR or CIFRE theses).

16.4.2 Research valorization and transfer

As outlined previously, a significant portion of our research activities is conducted in partnership with industry. With digital transformation and the implementation of AI, particularly in visual and multimodal systems, becoming a priority for many companies, our partner list spans a wide range of sectors (e.g. aeronautics, camera manufacturing, security, entertainment, social networks). Among the multiple CIFRE PhD projects, our project with DXOMark exemplifies successful scientific valorization. The learning-based camera quality assessment technique developed during this project was implemented in production by a dedicated engineering team and is now integral to the company's daily product operations. The methodologies developed in this PhD have contributed to the establishment of an AI team within the company, which is now actively working on applying this research to various other use cases.

Regarding participation in the drafting of standards, Jean Le Feuvre has made a notable contribution, with a total of 87 standardization contributions resulting in 44 documents and 12 international standards, and 26 patents or extensions. Attilio Fiandrotti and Jean Le Feuvre have also worked on Prématuration projects supported by IP Paris in 2019 in order to include recent streaming algorithms into the GPAC project.

16.4.3 Science popularization

Our team has led several communication initiatives oriented toward the general public to raise awareness about deep fakes: we collaborated with the YouTube channel *2 Minute Papers* to produce a [video](#) that explains our method for video generation [548] to the general public. The video has successfully garnered 1.1 million views. Stéphane Lathuilière has also participated in a [podcast](#) about Deep Fakes and assisted a journalist from Usine Nouvelle in composing an [article](#) about image generation, addressing the significant intellectual property concerns it raises.

16.4.4 Synthetic self-assessment

Opportunities. With the advent of Large Language Models (LLM) and multimodal models across diverse fields, we anticipate a significant growth in demand within the coming year.

Strengths. Our close connections with industry and our deep comprehension of practical applications are key assets. Our scientific emphasis on multimodal learning, along with our extensive technical expertise and scientific recognition, places us in a prime position to achieve high societal impact.

Weaknesses. Bureaucratic complexities, especially those related to facilitating internships for PhD students, hinder our opportunities to kickstart new collaborations with industrial partners. Time constraints, stemming from the administrative and teaching responsibilities of our professors, limit our ability to undertake extensive public communication initiatives and, more broadly, affect our capacity for scientific dissemination.

Threats. The constant influx of requests threatens to divert our attention from high-quality research. We must learn to decline many requests to dedicate enough time to research.

Chapter 17

Self-assessment of S²A team

17.1 Profile, Resources and Organization

17.1.1 Scientific objectives

Whether for prediction, decision-making, or interpretation purposes, the statistical analysis of data collected using modern technologies raises a wide variety of methodological issues, related to their great complexity (e.g. high-dimensional, structured, heterogeneous/multiscale, massive, incomplete/censored data, data streams, audio signals, text, weak signals and rare events), which need to be addressed to design more "intelligent" machines/devices (artificial intelligence). An abundance of new applications such as health monitoring of complex infrastructures, recommender systems, chatbots, machine listening and opinion mining, the availability of massive data samples (Big Data), and technological constraints inherent to information acquisition and access (e.g. sensor networks, IoT, distributed file systems) and to computation (e.g. infrastructures for massively parallelized/distributed computation, online processing) and challenging societal expectations (fairness, bias management, robustness/reliability, privacy preservation, energy frugality) has put pressure on the scientific community to elaborate new AI methods and algorithms. The development of these new approaches rests in various fields such as probabilistic modeling, statistical learning, simulation, optimization and signal processing. Rallying expertise in all these fields, more complementary today than ever, the team S²A has been committed to developing algorithms and concepts for AI. The team has structured itself around four intertwined topics, according to which its research activities are subsequently described.

- Probabilistic Modeling and Mathematical Statistics
- Machine Learning and Optimization
- Audio Data Analysis and Signal Processing
- Social computing

The S²A team is dedicated to producing sound methodological research in the four research areas listed above, in response to some of the challenges raised by the nature and format of modern data and to high societal expectations about the development of efficient, reliable and ethical data-based artificial intelligence solutions.

Since its move to the Saclay Plateau, the S²A team has taken advantage of a favorable environment for the development of its research activities, offered in particular by IP Paris. In line with its multidisciplinary positioning, its members are actively involved in the IDIA and mathematics departments of IP Paris, taking part in related scientific activities and boards. Professor d'Alché directed the labex DigiCosme between 2018 and 2019, with the team also participating in the labex LMH, and the Foundation FMJH since 2023, as well as in the organization of regular seminars within the Paris-Saclay ecosystem (e.g. sénaire palaisien de statistique, program PGM0),

in addition to involvement in joint initiatives such as the interdisciplinary centers (Hi! PARIS, E4C, CIEDS) set up over the period. In particular, the team is a key partner in Hi! PARIS, the interdisciplinary center dedicated to AI, plays an active role in its ongoing activities (e.g. operational management, scientific co-supervision, and management of the engineering team). The team is also highly committed to teaching at the Saclay campus. In particular, it provides numerous courses in the master programs MVA (ENS Paris Saclay) and Data Science (IP Paris) and is especially active in the doctoral school EDMH.

The enthusiasm for machine learning, spreading to nearly all fields, has created a context conducive to the activity of S²A, which has successfully responded to numerous dedicated calls for projects at both national and European levels (e.g. ERC, Innovative Training Network, ANR, PEPR IA, Ellis network).

While the team is a key player in a diverse range of national and international collaborations, it is also involved in joint initiatives within Télécom Paris: its skills and expertise are particularly sought after in cooperation with other departments e.g. the co-supervision of PhD theses with the INFRES/Comélec/SES departments, and the project Operational AI and Ethics.

In addition to academic collaborations/projects, the team has forged links with many companies/institutions (e.g. Idemia, Deezer, Air Liquide, ANSSI, EDF, Airbus) through joint responses to European/ANR project calls, bilateral contracts and CIFRE PhD theses, while also developing long term partnerships through the industrial chair 'Data Science and Artificial Intelligence for Digitized Industry and Services' (Safran, Valeo, Idemia, Engie, Airbus DS) and the joint laboratory 'LISTEN' (Valeo, Orosound, Bruitparif and Music World Media) in particular. These connections with industry are especially useful for the design of continued education programs, in which S²A is deeply involved (e.g. Advanced Master's in Big Data AI; Data Scientist in AI Certificates).

The scientific activities of the team embody technology transfer and development (projects funded by e.g. BPI, SATT), through the licensing of patents and spin-off projects.

They also include the popularization of sciences, with the writing of various articles or reports, shedding light on issues relating to the impact of AI and Data Science on society and the economy, for instance, (e.g. The Conversation, Fondation Abeona, magazine FNAC), participation in radio programs (Radio France) and the organization of exhibitions (e.g. maison Poincaré).

17.1.2 Resources

Human Resources. As demonstrated by its scientific production, the team has the critical mass to work on all four topics previously listed.

Team leader: Stephan Cléménçon.

Faculty Roland Badeau (Full Professor) - Pascal Bianchi (Full Professor) - Gérard Blanchet (Emeritus) - Maria Boritchev (Associate Professor, September 2023-present) - Maurice Charbit (Emeritus) - Chloé Clavel (Associate Professor, September 2019, Full Professor, October 2019-September 2023) - Stephan Cléménçon (Full Professor) - Florence d'Alché-Buc (Full Professor) - Radu-Alexandru Dragomir (Associate Professor, December 2023-present) - Slim Essid (Full Professor) - Olivier Fercoq (Associate Professor, September 2021, Full Professor, October 2021-present) - Mathieu Fontaine (Associate Professor, September 2021-present) - Robert M. Gower (Associate Professor, September 2021) - Yves Grenier (Full Professor, March 2018; Emeritus) - Ekhine Irurozki (Associate Professor, September 2020-present) - Yann Issartel (Associate Professor, September 2022-present) - Hicham Janati (Associate Professor, September 2021-present) - Matthieu Labeau (Associate Professor, September 2019-present) - Charlotte Laclau (Associate Professor, September 2022-present) - Laurence Likforman-Sulem (Associate Professor) - Pavlo Mozharovskyi (Associate Professor, September 2018-present) - Geoffroy Peeters (Full Professor, September 2018-present) - François Portier (Associate Professor, September 2021) - Gaël Richard (Full Professor) - François Roueff (Full Professor) - Joseph Salmon (Associate Professor, September 2018) - Anne Sabourin (Associate Professor, September 2022) - Umut Simsekli (Associate Professor, October 2020) - Giovanna Varni (Associate Professor, October 2022).

Associate Professors A. Bellet, P. Bertail, C. Clavel, D. Ernst, S. Gentric, R. Gower, O. Jelassi, F. Portier, A. Sabourin, G. Varni.

Non-permanent human resources: PhD students, post-docs, engineers & interns

Non-permanent staff 2018-2023					
Year	Total	PhD students	Post-docs/Engineers	Internships	Invited
2018	62	39	14	4	5
2019	58	39	8	10	1
2020	63	34	10	17	2
2021	73	42	19	10	2
2022	72	39	20	12	1
2023	90	48	26	12	4

Equipment - Computing Facilities. The team manages a multimedia studio and an anechoic chamber to conduct experiments. Regarding computation, it uses pooled resources, at the local and national levels (LTCI/IDS cluster, Jean Zay).

Although the team has no recurrent funding, it safeguards its financing by diversifying its sources (public calls for projects, bilateral contracts, sponsorship) and by developing long-term initiatives (e.g. the industrial chair DSAIDIS 2019-23, prolongation of the chair MLBGD 2014-18, the joint laboratory Listen).

2018-2023 (K€)							
	2018	2019	2020	2021	2022	2023	Total
Public National	498	636	497	505	493	991	3,620
International	243	300	300	287	101	393	1,624
Partnership & Transfer	1,142	699	1,047	1,025	944	1,294	6,152
Total	1,883	1,635	1,844	1,817	1,538	2,678	11,396

TABLE 17.1: S²A financial resources.

17.1.3 Synthetic self-assessment

Opportunities: The research topics of S²A reflect the spirit of the times. In reality, machine learning (AI), probabilistic modeling, and signal processing are not new fields of research. Statistical data analysis has a very long history and its development has been stimulated by various emerging fields of application and the ever-growing availability of data (e.g. social sciences, agronomy, industrial quality control, econometrics, insurance, epidemiology, environmental sciences, etc.). However, the digital information boom that goes hand in hand with recent technological advances in data collection and management (e.g. web, IoT, mass spectrometry, distributed platforms), offers new perspectives in many areas of human activity (e.g. transportation, energy, health, commerce, insurance), posing major scientific challenges for each sector concerning the exploitation of these data, which in turn calls for increased interdisciplinarity. The field now referred to as Data Science has emerged precisely in response to the complexity of modern data, to meet the need of increased automation and computational efficiency, to design increasingly "intelligent" systems (AI), capable of interacting with their environment in a reliable, trustworthy, and ethical fashion. Among these data, social data are ever more present and raise new scientific challenges in terms of machine learning methods, social signal processing, and natural language processing.

Strengths: To ensure that research in AI and Data Science has a high impact, theory and practice must go hand in hand. In particular, partnerships with industry and services through the development of chairs, joint laboratories, bilateral contracts, etc. are vital. The guiding hand of practical applications through such partnerships together with fundamental methodological research is the way to guarantee lasting impact and value creation. In this regard, the size and span of activities of the team from theory to applications are clear strengths and allow the team to have both impact and visibility in its community and beyond.

Weaknesses: Despite the recent strengthening of the presence of additional complementary skills to address challenges in machine/deep learning and data science through the recruitment of the young associate professors P. Mozharovskiy (machine-learning and computational statistics), M. Labeau (NLP), E. Irurozki (machine learning and computational statistics), M. Fontaine (machine listening and signal processing), H. Janati (machine learning and optimal transport), Y. Issartel (nonparametric statistics), C. Laclau (trustworthy and ethical machine learning) M. Boritchev (NLP) and R. Dragomir (frugal optimization and machine learning) and of the senior researcher G. Peeters (deep learning for audio signal processing) as full professor, the team has witnessed a significant turnover with the departures of members involved in all the research topics (J. Salmon, U. Simsekli, F. Portier, R. Gower, A. Sabourin, G. Varni, C. Clavel). While the size of the team may represent a risk, the *pivotal* organization of the team around open "scientific topics" (Machine learning, Audio data, and Signal Processing, for instance) with their scientific activities and seminars is a means on the one hand to mitigate the risk of dispersion and on the other to facilitate collaboration within S²A and more generally within LTCI. The other side of the coin is the high level of requests made to the senior members of the team concerning committees, expertise, co-supervision, publicity, and so on.

Threats: Furthermore, although socioeconomic expectations are very high in this field, to avoid harmful dispersal one must be careful to distinguish between what falls under development tasks (in this regard, our role essentially consists of training talented graduates), what comes within the competency of expertise and what comes under research, which should be based in the long run on well-balanced academic and industrial partnerships. Beyond the aspect of careful scientific positioning, the numerous professional opportunities offered by the private sector or certain public competitors represent a major threat to the sustainability of the team.

17.2 Attractiveness

17.2.1 Scientific reputation and contributions

International/National Recognition The team enjoys a high degree of international recognition, hosting the ERC senior project HI-Audio led by Gaël Richard. Florence d'Alché was the program co-chair of NeurIPS 2019 and is a member of the ELLIS board (ellis.eu). Professors Essid, Peeters, and Richard organized the 2018 ISMIR conference (general chairs) at Télécom Paris. Prof. Peeters served as the president of the ISMIR society (2020-2023). Professor Richard was the chair of the IEEE TC on Audio, Acoustics and Signal Processing (2021-2022). Regarding the top venues in Machine Learning, AI, and Signal Processing, several members of the team serve each year as senior area chairs, and area chairs or are members of the program committee of these conferences. Several members of the team also serve as editors or action editors for a variety of peer-reviewed international journals: JMLR, IJDAR, JMLR, JOTA, IEEE Signal Processing Magazine, TISMIR, IEEE TAC, and IEEE PAMI. The team plays an active role in Hi! PARIS, the interdisciplinary center dedicated to AI (academic co-management by S. Cléménçon and scientific co-supervision by G. Richard). F. d'Alché ran the Labex DigiCosme between 2018 and 2019.

Members of the team are regularly invited to give talks and keynote lectures and have organized or co-organized various conferences (e.g. ICPR2022 and ECML 2023 workshops) and workshops (e.g. FDAR@ICDAR2021) in addition to participating in the organization of regular seminars in the Paris-Saclay ecosystem (e.g. sémaire palaisien de statistique). Several doctoral students have received prestigious awards (e.g. 2nd IP Paris prize in AI awarded to P. Laforgue in 2019, Dodu

SMAI prize awarded to A. Barakat in 2020). Several members of the team have been distinguished by the granting of awards during the period, Professor Richard was awarded the Grand Prix IMT de l'Académie des Sciences in 2021, Prof. Cléménçon won the second Joseph Fourier prize in AI in 2018.

17.2.2 Staff hosting policy

A reliable indicator with regard the attractiveness and proper functioning of the team is undeniably the speed at which recruits defend their habilitation thesis (4 or 5 years on average after their recruitment). Reduced teaching loads, smooth integration into projects directed by more experienced members of the team, and the co-supervision of PhD students all contribute to recruits quickly gaining autonomy within S²A. On the other side of the coin, a rapid turnover is evident, with the departure of young senior members to other higher-level or subjectively more appealing positions. Hence, permanent (associate professor) positions are frequently opened up within the team (once a year at least over the period under review, and up to three times in 2022). The international visibility of the team combined with the personal networks of S²A's members and proactive publicity among the targeted research communities enables us to attract a high number of outstanding candidates (on average, several dozen for each open position). As part of the recruitment process, about ten candidates are invited to visit the team and give a seminar, of whom five are then shortlisted by the team with the help of external independent experts to be interviewed by Télécom Paris's recruiting committee. In most situations, the candidate ranked first has taken the position, which may be interpreted as another sign of the team's attractiveness. Regarding the massive recruitment of young (PhD and post-docs) researchers by the team, a distinguishing feature is its diversity (local and international) and quality. This may be partly explained by the outstanding commitment of the team to teaching at the master's level, to the PhD track program of IP Paris, and its scientific networking activities (*e.g.* ITN, Ellis network). In addition to the regular (weekly) thematic seminars organized by S²A, the team often welcomes visiting researchers (*e.g.* J. Leroux C. Weiss, K. Yoshii, H. Kadry), to collaborate on joint research projects or simply to enrich its scientific culture. Prof. Juho Rousu (Department of Computer Science, Aalto University) spent 2 months with us in 2019, and this visit initiated the co-supervision of a Master then a PhD student related to graph prediction with surrogate regression methods. Professor Bharat Sriperumbudur (Department of Statistics, UPenn) visited the team in December 2023.

Thanks to the Hi! PARIS center, the team also includes Prof. D. Ernst (Université de Liège), an expert in reinforcement learning and its applications to electricity pricing, as a permanent guest since 2021.

17.2.3 Success in competitive calls for projects

The team finances its numerous internships, PhD students, post-docs, and engineers, as well as its light equipment and operating costs through successful applications to a wide variety of competitive calls for projects. This great diversity of funding sources (sponsorship, public national/European calls, bilateral contracts) includes:

- ITN: MIP-Frontiers (<https://mip-frontiers.eu/>), New Frontiers in Music Information Processing; ANIMATAS (Advancing intuitive human-machine interaction with human-like social capabilities for education in schools)
- ERC advanced, HI-Audio (<https://hi-audio.imt.fr/>) Hybrid and Interpretable Deep neural audio machines
- Industrial chair Data Science and AI for Digitized Industry and Services (<https://datascienceandai.wp.imt.fr>)
- Joint laboratory LISTEN (<https://listen.telecom-paris.fr/en/>), A research laboratory dedicated to machine listening

- ANR projects: International project ANR/Tubitak FBIMATRIX on "Parallel and Distributed Markov Chain Monte Carlo for Bayesian Inference in Matrix and Tensor Factorization Models"; ANR JCJC SAROUMANE; ANR PRCE LIMPID; ANR PRC AQUA-RIUS; ANR JCJC MAOI; ANR JCJC GRACE; ANR JCJC APDO; ANR PRC REVITALISE; ANR PRCE ApI
- PhD grants and post-doc fellowships from ANR-IA, PEPR IA, Labex LMH/DigiCosme; Hi! PARIS center
- BPI (PIA) projects Espresso, Audible, Geolytics, e-logistics
- CIFRE theses, with *e.g.* Criteo, Idemia, BNP, ANSSI, Nokia Bell Labs, Valeo, PSA, Deezer, Thales, Bridge.audio, Sony CSL, Orosound, smart Impulse, IBM, OnePoint, Air Liquide, TotalEnergies ...

17.2.4 Equipment quality and technological skills

The S²A team is well equipped for a wide range of applications related to audio and multimedia. This includes a brand new 40m³ anechoic chamber and a fully equipped recording studio with multi-sensor, multimodal capture facilities (50 fps video cameras, kinect, motion sensors). TPT has acquired a large number of musical databases (*e.g.* ENST-Drums, MAPS) amounting to several GBytes of annotated data and has also developed an integrated and centralized platform for database and software tools. TPT open-source software tools include the audio feature extraction toolbox (YAAFE). The available in-house computing resources include a 20-node cluster on Debian with P100 or V100 GPUs, 50 freely accessible rack servers, network storage resources with a volume of over 80TB, a highly available research IP network (R2) offering direct internet connectivity, a Big Data Hadoop platform with a storage volume of over 50TB, and an OpenStack cloud computing platform enabling the creation of up to 500 virtual machines. In addition, the research team has direct access to the Jean Zay Supercomputer.

17.2.5 Synthetic self-assessment

Strengths: Its academic excellence being well-recognized, the team enjoys a high level of international visibility. Positioned on booming methodological topics, it has built a real ecosystem, with networks at its disposal, progressively reinforcing its integration capacity.

Weaknesses: The main difficulties faced by the team are due to problems accessing the Palaiseau site, accommodation issues on the IP Paris campus, the absence of partnerships with national research organizations, and a certain degree of institutional instability.

Opportunities: Playing a key role in the set-up and management of the Hi! PARIS center, the team has taken full advantage of its involvement, by obtaining funds for the recruitment of an associate professor, PhD theses, and post-docs, and by leveraging the support of its engineering team to produce more visible reproducible research, in the form of open-source software.

Threats: Because its scientific positioning balances upstream and technological research, the team competes with both the academic and industrial sectors, threatening its sustainability.

17.3 Scientific Production

17.3.1 Qualitative analysis

Although also featuring the elaboration of (labeled) databases (*e.g.* audio or multimodal databases), open-source software and patents (4 over the period 2018-23), the vast majority of the S²A team's scientific production consists of publications in top-tier journals and conference proceedings, related to each of the four topics structuring its activity: typically, journals such as Annals of Statistics, Bernoulli, Electronic Journal of Statistics, SIAM Journal of Optimization, JMLR, IEEE Signal Processing, IEEE PAMI, IEEE Transactions on Audio, Speech and Language Processing, IEEE Transactions on Affective Computing, Transactions of the Association for Computational

Publications 2018-2023 (source HAL)				
Year	Total	Journal	Proceedings	Chapters/Reports
2018	90	33	37	20
2019	106	25	56	25
2020	86	20	57	9
2021	114	22	51	41
2022	91	21	52	18
2023	81	18	39	24

TABLE 17.2: Scientific output of the S²A team.

Linguistics, and proceedings of conferences such as ACL, EMNLP, ICASSP, IEEE SSP, ISMIR or ACII. Furthermore, as *methodological Machine Learning* is arguably the cornerstone of S²A’s activity, a significant number of S²A’s publications appear in the proceedings of conferences such as Neurips, ICML, AISTATS, ICLR AAI, ECML or ACML.

Topic - Probabilistic Modeling and Mathematical Statistics

Contributors: Stephan Cl  men  on, Florence d’Alch  -Buc, Ekhine Irurozki, Pavlo Mozharovskyi, Fran  ois Portier, Fran  ois Roueff, Anne Sabourin

The team has maintained a recognized methodological expertise, specifically in probability and statistics, dedicated to data exhibiting specific dependence structures (*e.g.* spatial data, time-series, survey data, extremes), which enables it to successfully address a wide variety of applied problems.

Statistical methods for ranking, anomaly detection and extremes modeling.

With expertise in extreme value theory (EVT) being a key feature of the S²A team, certain members actively contribute to this field of research, in particular through their work on applications of extreme value theory to the tasks of visualization and anomaly clustering [759] and classification [707], as shown in the work by A. Sabourin (habilitation in 2021 [866]) and her collaborators. While EVT models the behavior of extreme events far from the center of the distribution, another line of research addresses a non-parametric view on the observations in the tail of a distribution from the perspective of data depth. This addresses both methodological [843] and application [778] aspects, as demonstrated in research carried out by P. Mozharovskyi (habilitation in 2022 [844]) and his collaborators. The methodology of the statistical data depth function, based on data geometry being purely non-parametric and robust, enables the defining of rank- and order-based inference for data in different spaces (including Euclidean, spherical, curve and graph data) without making explicit distributional assumptions, and thus finds numerous applications in a wide range of areas *e.g.* data visualization, classification and clustering, statistical inference, and anomaly detection. With rankings themselves being an important data type, members of the team pay particular attention to ranking aggregation [714, 820] and modeling [771], for instance, as well depth-based inference [803] for ranking data. Studying robustness to anomalies, *e.g.* for a median-of-means approach [875, 710], team members further show that non-parametric methods (and in particular data depth) also prove fruitful when applied to anomaly detection tasks, in particular in the functional setting [709]. More precisely, providing a robust estimate (*i.e.* not taking anomalies into account during estimation), the data depth function enables the differentiation of normal score data (possessing high depth) from anomalies (taking low depth values). With survival analysis being a long-recognized classical statistical problem, the team’s work also covers this topic. More precisely, members of the team introduce estimators based on conditional normalizing flows [762] and study the context of empirical risk minimization for a censored regression set-up [727].

Statistical inference for time series and dependent data.

Dependence across space and time in data sometimes bears the essential information in the data itself. This is essential to construct adequate predictors and to carry out meaningful analysis of their theoretical properties. This topic is mainly treated from a statistical point of view by the team, more specifically by studying the problem of statistical inference (estimation or prediction) for specific stochastic models, based on the team's expertise in probability and statistics. Nevertheless, many works on this topic are related to multiple practical problems in signal processing, machine learning, or industrial monitoring.

Parametric statistical inference for dependent data across time or space has been explored, with an emphasis on investigating settings involving general classes of time series. We obtained these general results in various contexts: 1) the class of partially observed Markov models in the fully dominated case ([784]) or in the case of observation-driven models [785, 872]), which is only partially dominated, requiring a very specific analysis for establishing ergodicity; 2) the class of long memory models in the non-linear case ([786]) or in the infinite-dimensional case ([790]).

The latter reference is part of a CIFRE thesis [789] with the company EDF, where the data takes the form of a time series of daily curves which motivates a series of studies in this specific context ([791, 792, 793]) with applications in the analysis of electricity consumption at industrial sites.

Another aspect of our research dealing with complex data is in line with recent trends in machine learning. Firstly, we obtained new probabilistic bounds used for establishing learning rates in risk minimization that apply beyond the usual i.i.d. assumption ([737, 873]). Secondly, in the context of the thesis [775], we derived new algorithms for the variational inference based on α -divergence ([776, 777]). Thirdly, we provided new theoretical non-parametric analyses for locally stationary dependent observations, for adaptive linear prediction ([864]) and spectral analysis of point processes ([865]). Other types of dependence have also been considered. In [764], a non-asymptotic theory for statistical learning based on Markovian data has been elaborated, while the case of spatial data is dealt with in [873] and exponential inequalities for survey data have been proved in [737].

Stochastic approximations and optimization.

The team is deeply involved in the study of Monte Carlo methods, and develops techniques that allow approximate estimates in the contemporary context of large data to be obtained. For Monte-Carlo approaches, evaluating integrals is a powerful tool which offers an alternative to deterministic integration techniques. In particular, the team studies the behavior of such methods based on kernel smoothing, addressing the non-asymptotic perspective [768]. Furthermore, Monte Carlo integration with variance reduction through control variates is another focal area of the team's research efforts [830]. Theoretical analysis is also represented by works on Rademacher complexity for Markov chains [738] as well as a study of asymptotic optimality for adaptive importance sampling [779]. In optimization theory, gradient descent techniques are an attractive instrument that enables the rapid achievement of a (local) minimum of the optimizable functional. In this context, the problem of gradient estimation is of high importance and is studied by certain members of the team from a non-asymptotic point of view [713]. Moreover, a variant of stochastic gradient descent, a major optimization tool in machine learning that allows for a flexible sampling of coordinates, has been developed [829]. The use of adaptive survey schemes for sampling mini-batch samples in SGD has also been proposed and studied in [763].

An alternative to gradient descent algorithms, especially in a non-convex setting, is to rely on maximization-minimization algorithms. We proposed and studied new algorithms of this kind in the context of variational inference based on α -divergence minimization ([776, 777]). As mentioned previously, data depth methods are renowned for their attractive statistical properties, such as non-parametricity, robustness, desirable invariances, *etc.*, while efficient computation of data depth, as well as upper-level sets, remains an ongoing challenge. Members of the team contribute to this issue by, first, the development of exact algorithms for computing Tukey depth trimmed regions (upper-level sets of the celebrated halfspace depth function) [833]. Secondly, several zero-order optimization algorithms have been proposed or adapted to the depth computation problem (being sometimes of combinatorial complexity) to provide an efficient approximation of the depth estimates [794]; their corresponding theoretical guarantees have also been studied, in the case of

randomized approximation algorithms [845].

Topic - Machine Learning and Optimization

Contributors: Pascal Bianchi, Chloé Clavel, Stephan Cléménçon, Florence d’Alché-Buc, Slim Essid, Olivier Fercoq, Robert M. Gower, Ekhine Irurozki, Ons Jelassi, Charlotte Laclau, Laurence Likforman-Sulem, Joseph Salmon, Anne Sabourin, Gaël Richard.

The team develops research activities in Machine Learning with both a solid theoretical grounding and a strong motivation to solve practical issues discussed with the companies with whom the team collaborates. A common research interest for several researchers in the team concerns the design of novel methods to solve newly defined tasks that go beyond classification and regression such as learning to rank, structured output prediction, outlier detection, quantile regression, and link prediction. However, we also address challenges that have become prevalent as a result of the massive use of machine learning techniques: reducing bias, ensuring the fairness of model outputs, designing robust models, providing explanations for output, and protecting privacy. Optimization, as a key to learning, is another main topic of interest for the team. We are committed to proving the theoretical properties of the optimization algorithms that we design. Our interests range from saddle point problems for which we develop primal-dual algorithms, to the improvement of stochastic gradient descent algorithms and distributed optimization algorithms. The know-how we develop in convex and non-convex optimization also directly impacts certain issues in Machine Learning such as feature selection in high-dimensional spaces and reinforcement learning.

Numerical optimization.

Stochastic gradient. For the training of neural networks, the most efficient methods process data points one by one. In a series of works, we have studied the convergence of the stochastic gradient descent method for the non-smooth and non-convex functions that appear in neural networks. One major difficulty is that the expectation of the backpropagation output may not be an element of the Clarke subdifferential of the objective function. Our proof techniques allowed us to overcome this difficulty and we showed that the algorithm converges [743]. We also studied the more complex stochastic heavy ball [870] and ADAM algorithms [730] with the same level of generality. Another question of interest is the quality of the stationary point reached by the method. We showed that even for non-smooth functions, stochastic gradient descent generically converges to a local minimum. [744]. Finally, in the case of convex functions, we proposed improved step sizes and an analysis of why nontrivial minibatches fasten convergence [802].

Stochastic proximal operators and Hessians. Our deep understanding of stochastic algorithms allowed us to analyze more complex oracles than stochastic gradients. We developed stochastic proximal point methods, which can manage explicit constraints without using a (difficult to tune) penalization and are faster for non-smooth objective functions [742]. We also considered second-order oracles that compute estimates of the Hessian matrix and were able to propose a much more general convergence proof result than previous works [885].

Reinforcement learning. Optimization algorithms in reinforcement learning are computationally demanding and have many hyperparameters. Indeed, the observations are not identically distributed and have often a very large variance. Improving their analysis can have a tremendous impact on final behavior and the guarantees we have about it. In particular, we studied Vanilla Policy Gradient [884], a target-based actor-critic algorithm [731] and bandit methods for generalized linear models [795].

Randomized algorithms for saddle point problems. Based on the recently introduced smoothed duality gap, we designed and analyzed new primal-dual algorithms for the resolution of convex optimization problems with constraints. This tool provides a general framework to derive convergence speed results from inequalities on the Lagrangian function [877]. We were able to analyze randomized primal-dual coordinate descent [720] as well as propose a new improved variant that enables larger step sizes [719]. All these methods have been implemented in an open-source package that allows the user to access all of their extended modeling power [796]. We also studied a

combination of the Frank-Wolfe method with Lagrange multipliers and its application to large-scale semidefinite programs [887]. Finally, we studied saddle point problems beyond convexity and showed that, because of the existence of limit cycles, convergence can only be guaranteed for large enough step sizes [858]. This goes against the usual intuition that good optimization algorithms should try to follow the underlying dynamical system as closely as possible.

Optimization on distribution space. We proposed a sample-feature alignment method based on regularized optimal transport [876]. It is more robust to outliers than previously proposed methods and can deal with unbalanced data sets. We also worked on Stochastic mirror descent for kernel density estimation. In the context of Monte Carlo methods, we proposed an adaptive importance sampling algorithm, to approach a target density using only non-normalized density evaluations. We developed it on "mirror descent" applied to Kullback-Leibler divergence, reducing significant weight variance. Another topic of interest is the long-run convergence of interacting particle systems. We study the convergence of algorithms updating a number n of variables (particles). This covers various applications in machine learning, such as the stochastic gradient algorithm for neural networks, or the Stein Variational Gradient Descent (SVGD) in Monte Carlo methods. Analyzing systems as the number of particles tends to infinity reveals global convergence properties towards the invariant measures of a certain McKean-Vlasov process.

Analysis of benchmarks. Selecting the best-performing algorithm from a benchmarking collection of tasks is crucial across various practical applications, notably in ML and optimization. However, this decision-making process is problematic, particularly when dealing with randomized algorithms or when the goal is to choose the most suitable algorithm based on multiple criteria, which is the usual setting in ML and optimization. With this in mind, we have proposed a visual tool based on hypothesis testing procedures for the comparison of two algorithms in [724],[723]. We also propose a methodology to compare the performance of two algorithms when they are run on different machines in [725]. In [818] we propose a benchmarking algorithm to decide the best performing algorithm in a multi-criteria setting on a large number of algorithms with application to Natural Language Processing.

Trustworthy machine learning.

Bias and fairness in AI. Before the Big Data era, information was essentially collected through carefully designed survey sampling schemes, generally a lengthy and expensive process. In contrast, data are now easily available on a massive scale, irrespective of their future use for specific statistical learning tasks. This dramatic increase in the availability of datasets has occurred at the expense of poorer control of the acquisition process and a greater degree of uncertainty about their representativeness. Novel machine learning methods tailored to various situations, where training data are not distributed according to the target distributions, have been proposed and analyzed in a series of works: see [763] about the case where source data are collected using known survey schemes; [728] when training samples are censored; [769, 766, 767] for other situations where the form of the biasing mechanism is known, and [712] for methods aimed at learning the biasing mechanism in the presence of auxiliary information. AI systems that make significant decisions for humans, regarding for instance credit lending, medical diagnosis, biometric identification, or recidivism prediction should ensure they do not penalize certain segments of the population (e.g. defined by gender, ethnicity, age). In [711], we have developed novel fairness concepts in similarity learning and strategies to optimize them without damaging accuracy, while an original approach to fairness, based on representation learning, has been proposed in [765], with promising applications in the design of fair facial recognition systems.

Robust/reliable machine learning. Statistical learning by Median of- Means (MoM) offers an appealing alternative to the principle of Empirical Risk Minimization in machine learning when data are corrupted. We have introduced a robust version of Wasserstein distance leveraging MoM and theoretically studied its robustness [875]. In [710], we have provided bounds describing precisely how robust such methods are and have extended this approach to situations where the risk is of the form of a U -statistic (e.g. in metric learning, clustering, ranking) in [708]. The idea of *robust consensus* has also been extended to ML with ranking data in [706, 803, 819, 818]. On

another note, we have endowed a structured prediction model with the ability to abstain in [801] leveraging a new loss in a surrogate regression approach. We could apply the model to accurate opinion prediction.

Explainable machine learning. To tackle interpretability in deep learning, we have proposed a novel framework to jointly learn a predictive model and its associated interpretation model in [850]. A dictionary of high-level attribute functions is learned to interpret the decisions of the predictor. The originality of this approach lies in the nature of the attribute functions that directly rely on hidden layers of the prediction. The predictor and the interpreter jointly learned benefits from a common loss function. The versatility of the framework means it can cope with different input modalities (image, audio signals) and has been adapted to classification and multi-label classification [821].

Frugal learning. The sustainability of AI not only involves trustworthiness and reliability but also requires a drastic reduction in its energy consumption and carbon footprint. While ML algorithms have been mainly driven by performance criteria for many years, frugality is now a key asset when it comes to its implementation in production. Learning efficiently under a low data regime requires a reconsideration of the definition of supervised learning. For instance zero- and few-shot learning call for more involved losses that enable the extrapolation of classes poorly represented during training. An original angle on few-shot learning both in classification, regression or sequence prediction consists of leveraging target variable embeddings based on Fisher score and probabilistic models for the output data's marginal distribution [782]. Another way to ensure frugality in a large data regime is to develop algorithms by design with low memory and reduced computing time requirements by exploiting low-rank approaches (see for instance, [748] in structured output prediction). Leveraging random projections, sketching approaches have been developed to develop frugal kernel machines going beyond the square loss and tackling the general class of Lipschitz continuous losses [715]. Similarly random Fourier features allow a scaling up of kernel methods and the tackling of large training datasets in real-world applications such as energy production forecasting in wind turbines [746].

Complex output prediction. In real-world applications, prediction tasks do not simply boil down to classification or regression. For instance, in forecasting problems, you may wish to predict the entire behavior of a device over time. We have developed a non-parametric framework that enables the tackling of regression with functional values for a wide variety of functional losses, especially those that exhibit a certain degree of robustness against noisy measurements and outliers. This set of tools is based on vector-valued reproducing Kernel Hilbert Spaces either leveraging a new class of representation theorems leveraging the duality principle [823] or deriving computationally tractable algorithms [824] to learn in vv-RKHS spaces. Another view to regression with functional values is to rely directly on a finite dictionary of functions and learn functions that predict projections onto this dictionary [745], again providing consistent estimators. Interestingly, even when the problem at hand is not natively regression with functional values, it can be relevant to exploit this tool to benefit from additional regularization tools. For instance, we have proposed in [823] to extend multi-task learning to *infinite task learning*, transforming any task defined by a continuous parameter into a functional regression problem using a Monte Carlo approximation of the functional loss, featuring novel applications in *quantile regression*. On a related but different note, we also developed a novel family of structured output prediction methods targeting the general family of applications wherein the output variable is a graph, a tree or a ranking among objects. For that purpose, we have leveraged surrogate regression methods based either on kernel-induced losses [822, 749], or optimal transport losses such as the Fused Gromov-Wasserstein distance [747]. In the latter, the surrogate regression scheme leads to an original end-to-end predictive model that directly predicts a graph as a weighted barycenter of template graphs. Whereas the contributions of the team in the field of machine learning for complex/structured data are mainly methodological and apply to generic problems, certain specific applications have been developed, concerning molecular biology or cybersecurity in particular, see *e.g.* [827] or [826].

Topic - Audio Data Analysis and Signal Processing (ADASP)

Contributors: Roland Badeau, Slim Essid, Mathieu Fontaine, Yves Grenier, Geoffroy Peeters, Gaël Richard, Umut Simsekli

The S²A team members involved in the ADASP research topic (Audio Data Analysis and Signal Processing) conduct research in machine learning for signal processing, mainly targeting *machine listening* applications. Machine listening, or *AI for sound*, may be viewed as the counterpart of computer vision for audio signals. It aims to endow machines with the capacity to understand, interpret and exploit audio signals, similarly to humans. It encompasses the general field of machine learning applied to audio analysis and synthesis, covering three main research sub-communities: speech processing, music processing (aka MIR¹), and acoustic scene analysis (aka DCASE²) sub-communities. As in many other domains, the general trend in machine listening has been marked by a clear paradigm shift towards data-driven methods based on machine learning, especially deep learning, which is now ubiquitous [855]. Apart from its focus on machine listening, LTCI's ADASP research also addresses problems in multimodal perception as well as other more general forms of signal processing (*e.g.*, electrical or physiological signals, especially electroencephalographic (EEG) signals). The applicative fields of the ADASP topic are thus diverse, ranging from environmental sound analysis [857], through speech processing [890], source separation and enhancement [867, 799, 840], to music content analysis, synthesis and transformation [761, 847, 754, 750, 880], as well as audio-driven multimodal data analysis [851, 753, 859]. A significant proportion of our research is performed as part of national and international collaborative projects which include for instance the joint laboratory LISTEN, involving industrial and institutional partners, the ERC project HI-Audio on hybrid deep neural audio machines, the BPI-France funded project Audible on the development of the next generation of smart hearables, the ANR-JCJC project SAROUMANE on deep bayesian neural networks for speaker diarization and the ANR AQUARIUS on audio quality description using differentiable audio FXs. In the following section, we further elaborate on our main research areas.

Audio and speech representation learning. Representation learning is a major topic for LTCI's ADASP researchers. Recently, the focus has been on two main research lines: i) signal processing-aware (aka hybrid) representation learning, and ii) self-supervised representation learning. As far as the former is concerned, we have aimed at learning interpretable projections in the form of parameterized filterbanks. For the case of source separation, we proposed new projections for the front-end [840] (Hilbert and Bedrosian kernels) and for the within projections of a Wav-U-Net [841]. Those enable a drastic reduction in the number of parameters for equal performances and facilitate the interpretability of the projections. As for self-supervised learning (SSL), several important research questions have been addressed. In [890] we have introduced a method to automatically select a group of pretext tasks among a set of candidates, given the knowledge of the downstream tasks to be solved. The method we propose estimates calibrated weights for partial losses corresponding to the considered candidate pretext tasks during the self-supervised training process. The experiments conducted on automatic speech recognition, speaker and emotion recognition, as well as musical instrument recognition, validate our approach, as the groups selected and weighted with our method perform better than classic baselines. Moreover, the techniques developed prove to be useful for selecting appropriate data augmentations for domain-adapted fine-tuning of self-supervised speech representations [889]. Furthermore, we have investigated the robustness of current SSL benchmarking approaches, showing that the choice of decoding architecture that maps the frozen SSL representations to the downstream labels is crucial [888]. Interestingly, it appeared that varying the architecture of the downstream decoder leads to significant variations in the leaderboards of most downstream tasks. More worryingly, our study revealed that benchmarking using limited decoders may cause a counterproductive increase in the sizes of the developed SSL models. Successful SSL solutions have also been developed for musical signal analysis: using audio/video co-occurrence to train audio projectors [859] for video-

¹Music Information Research

²Detection and Classification of Acoustic Scenes and Events

to-music recommendation, or using data augmentation with a novel equivariance loss to train a pitch estimator [863]. Moreover, interesting contrastive SSL variants were proposed for music segmentation and music structure analysis [750, 751]. In particular, we have introduced a contrastive SSL approach operating at different timescales to enable hierarchical structure analysis, given that different levels of segmentation can be considered equally valid for most musical pieces.

Source separation and enhancement. Source separation is one of the historical themes of LTCI, which pioneered research work in this area in the 1990s. The topic has received sustained interest in the period under review, in particular for speech and music applications, but also for energy load monitoring and EEG data analysis. For audio signals, we have considered the general, and realistic situation of speech/music source separation in noisy and reverberant environments in the so-called under-determined case (i.e. where the number of sensors is lower than the number of sources). To address this problem, it is necessary to integrate prior knowledge about the sources or the mixing process. For instance, percussive source models were built for drums separation [825] and flexible and generic heavy-tailed statistical models were also developed (citeSimsekli Icassp 2018, Fontaine-GSMFastMNMF 2021), including a new time-domain approach exploiting heavy-tail Student-t distributions to model the mixing process, which enables a significant improvement over classic approaches [828]. In other cases, we have further extended the concept of cross-modal source separation where the prior information can be derived from another modality such as EEG signals ([753, 755, 754, 752]), text (such as lyrics for singing voice separation [867]) or Video ([849, 788, 852]). In addition, we have recently started to investigate a novel path, so-called hybrid deep learning, combining data-driven and model-driven approaches in, for example, exploiting a source-filter model of singing voice for unsupervised music source separation ([868]). Another line of research has aimed at learning interpretable front-end representation in the form of parametrized filterbanks optimized for source separation [840, 839]. Another important research topic is speech enhancement, where we have considered in particular the problem of distributed speech enhancement in spatially unconstrained microphone arrays, examining a deep neural network-based mask estimation approach serving a distributed multichannel Wiener filtering system [799]. Concurrently, we have developed an activity on Non-Intrusive Load Monitoring (NILM), where the energy consumption of specific devices is estimated from the sole knowledge of global consumption measured at a given sensor. Our work focused on the less studied case of high-frequency large building load monitoring with new efficient methods exploiting Independent-Variation Matrix Factorization ([814, 815, 813, 816]).

Audio scene analysis. The LTCI has also performed work on audio scene analysis, especially targeting sound event recognition tasks. A first line of work has dealt with sound event detection in urban environments [722] focusing on the problem of domain generalization across multiple cities. We have also looked into augmentation techniques, which are particularly important in this field lacking training data, studying adversarial data augmentation [856]. Notably, LTCI's ADASP researchers have taken part in the organization of the DCASE 2023 challenge Task 4³ on "Sound Event Detection with Weak Labels and Synthetic Soundscapes and Sound Event Detection with Soft Labels". In the context of acoustic scene understanding, a pivotal research direction for robust machine listening is acquiring insights into sound propagation within enclosed spaces. For instance, in [718, 716, 717], the focus was on estimating reverberation parameters. These findings lay the groundwork for future research, serving as prior knowledge for more resilient machine listening applications such as automatic speech recognition or augmented listening, aiming at remixing the audio scene to enhance human perception and exploit it in either a real-world or augmented/mixed reality setting. Preliminaries studies have been performed in the LTCI to implement real-time speech recognition on target speakers using mixed-reality headsets [787, 871, 848]. Notably, aspects such as multimodal source separation and speech enhancement played a pivotal role in achieving this task.

Music information retrieval. Music Information Retrieval (MIR) has been a major topic for LTCI's ADASP researchers during the period under review, with the organization of its main conference ISMIR in 2018, its scientific program in 2019 and 2023, and the presidency of the

³<https://dcase.community/challenge2023/>

related international society from 2021 to 2023. MIR has also been the subject of two major EU projects: the MIP Frontier European training network which trained 15 PhD students across Europe and the recent ERC Hi-Audio led by one S²A member. MIR research in S²A relates to the development of new audio signal processing or machine learning (mostly deep learning [853]) models potentially including multi-modality (EEG [753] or Video [859]). Two core groups of MIR tasks are being developed in S²A. For music analysis, models are being developed for beat/downbeat [798], tempo/rhythm [797], pitch/multi-pitch [881], [863], structure estimation [751], [854], lyrics synchronization/transcription [878] and cover version detection [783]). For music processing/generation models, are developed for music timbre transfer [760], source separation [842], [770], [869] and generation (drum synthesis [847]). Multi-modal analysis is also studied through EEG-music [753] or video-music [859]. For all of these tasks, new models are being developed such as skip-chain CRF [798], zero-shot learning using generative models (differentiable source/filter model [869]), one-shot learning using conditioned VQ-VAE [760], metric learning using self-supervised-learning based on audio/video correspondence [859], equivariance siamese networks for metric learning [863], multi-label CTC for polyphonic alignments [881], novel triplet loss based on prototypes [783] or novel triplet mining algorithms based either on Self-Similarity-Matrix [751] or on hierarchical annotations [750], conditioning mechanism of U-Net based on FiLM layers for universal source-separation [842], complex-neural-network [797], generation using sequence of tokenized inputs - VQCPC-GAN - [846] -, novel positional encoding for transformers -relative to linear complexity - [834].

Topic - Social Computing

Contributors: Chloé Clavel, Florence d’Alché Buc, Slim Essid, Matthieu Labeau, Laurence Likforman, Giovanna Varni, Gaël Richard, Anne Sabourin

The Social Computing topic aims to conduct research around computational models for the analysis of social interactions. The key feature of this theme is its multidisciplinary: it implies interconnecting complex (e.g. psychological or sociolinguistic) theories of the social sciences with the formalism underlying machine or deep learning models for socio-emotional phenomena such as sentiments, emotions, stances, cohesion, trust or self-confidence. Given the more extensive availability of data, and following the tremendous development of computational models of language in the last years, the topic has retained a focus on language modality.

Human-agent interaction: from social signal perception to generation. We studied the processing of various social signals and emotions in human-agent interactions, for various applications. We developed weakly supervised machine learning models for the prediction of user engagement breakdown in human-robot interaction [734, 735], and improved on them by including contextual information [726]. In the context of the ANIMATAS (Innovative Training Network) project, we have been working on the development of social robots in education, proposing neural models for the analysis of people’s self-confidence [781] in an interaction. We also developed models enabling an understanding of when it is appropriate for a virtual agent to automatically perform appropriate communicative gestures [886] and to produce them [861]. Lastly, we investigated models of trust in multimodal user-robots interactions [817].

Modeling social-emotional phenomena in interactions. We have worked on modeling different aspects of interactions, mainly through several ANR projects. We proposed several improvements for opinion mining models [801, 800], a research direction we extended in the MAOI project, where we proposed novel architectures for dialog act prediction [773] and a large-scale model pre-trained on spoken dialog, as well as a dedicated benchmark [757]. In this project, we also contributed to multi-modal [772] and multi-lingual [756] models. The GRACE project aimed to develop a computational model of cohesion among humans able to integrate the task and social dimensions of cohesion, producing a multimodal dataset [835], in addition to several studies on predicting the dynamics of cohesion [837, 836]. Finally, we began investigating the most relevant features for persuasiveness [741, 732], and proposed a new dataset on public speaking [740], work

which will be continued in the recently launched REVITALISE project, where we will focus on training students in public speaking.

Tractable and explainable models for social computing. In terms of tractability, we have developed various strategies to deal with a prevalent issue in our field: the lack of annotated data. While we made several contributions to the annotation of socio-emotional phenomena [739, 807, 733, 879], we also worked extensively on frugal approaches, allowing efficient processing with very little annotated data. We proposed approaches that allow classification to label unknowns during training [805, 804, 780], that facilitate both domain and task transfer [806], or to deal with label uncertainty [838]. Lastly, we recently launched the CFTextAD (ANR) project, which will focus on textual anomaly detection: detecting rare or previously unknown phenomena in text.

The issue of the lack of explainability of machine learning and in particular deep learning models is even more acute for socio-emotional models, as the human states modeled are highly subjective. This research is still in its infancy: much remains to be done before we can truly explain and "control" the information contained in the models. In-depth analysis of the rationales for model decisions was explored through a post hoc analysis of multimodal models for job interview analysis [812]: in this case, we previously proposed a strategy to remove sensitive information from the model [811]. We also developed several methods to analyze, manipulate, and extract useful information from model's representations: using mutual information to disentangle the information contained in sentiment models [774], devising metrics to analyze traces of stance in contextualized word representations [874]. Finally, we have recently shown that gender cannot be predicted from handwriting signals [832].

17.3.2 Potential and dissemination strategy

The publications are shared homogeneously, across the four topics and among the members of the team (junior or senior). The sole difference possibly lies in the nature of the publications (publishing in journals rather than conference proceedings being considered the norm in probability & statistics, in contrast to the other topics). Because young faculty members may have a reduced teaching load and are invited to join forces with senior ones to work on collaborative projects or to co-supervise internships, PhD theses, or post-docs, their publication activity is facilitated. They usually complete their habilitation thesis around 7 to 10 years after their PhD diploma, which demonstrates the rapid development of our talents.

17.3.3 Scientific integrity, ethics and open science

Our papers are systematically posted on preprint servers such as HAL or Arxiv, to make them freely available. Whether in the laboratory or as reviewers or editors, we make sure that the research we carry out is fully reproducible. This is often done with a freely available code, hosted on a Github repository for instance. If necessary, the Hi! PARIS engineering team (<https://engineeringteam.hi-paris.fr>) can help us design scientific software and packages complying with the current standard so that it is made easier to use by other people, *e.g.* <https://github.com/hi-paris/structured-predictions> or <https://data-depth.github.io>.

Our team is involved in the production of public datasets and benchmarks that are made available to the research community. In particular, the team has contributed data for various machine listening and socio-emotional analysis tasks, including music and general audio data, scalp EEG data, simulated current and voltage data, and new textual or multimodal corpora of spontaneous human-human and human-agent interactions. The corpora and benchmarks are distributed via the Télécom Paris corpus distribution platform, Zenodo or Huggingface, and are listed here: <https://clavel.wp.imt.fr/corpora/> and here: <https://adasp.telecom-paris.fr/resources/>.

17.3.4 Synthetic self-assessment

Opportunities: The team's research topics are booming and a wide variety of calls for projects are available. Most of them are tailored to S²A's scientific positioning, involving methodological

research and expertise in specific applications.

Strengths: The team’s scientific production stands out for its quality (top journals and conferences), quantity and diversity (publications, patents, databases, open source code, demos).

Weaknesses: A lack of technological resources prevents us from addressing certain applied subjects (*e.g.* in NLP), forcing us to focus on certain other more methodological topics requiring less computing power and data.

Threats: The main threats identified are the huge turnover experienced by the team (the non-stop recruitment process being extremely time-consuming), the headhunting led by the high-tech sector and the level of requests (*e.g.* committees, collaborative projects, boards, etc.) to which the team (the senior members especially) is subjected.

17.4 Contribution of Research Activities to Society

17.4.1 Socioeconomic partnerships and interactions

Diverse industrial partners and modes of collaboration. As previously described, a significant proportion of our funding comes from partnerships with industry (sponsorship, bilateral contracts, collaborative projects, CIFRE PhD theses). As the digital transformation and the deployment of AI have been placed at the top of the agenda by most companies in a wide range of sectors, the list of our partners thus contains a high degree of diversity (*e.g.* health, energy, finance/insurance, transportation, security, entertainment, commerce). The DSAIDIS chair and the joint laboratory Listen permit enable long-term interactions with some of these partners (*e.g.* Idemia, Valeo, Airbus), which create a favorable context for more ad-hoc collaborations (*e.g.* ANR, CIFRE theses, BPI projects). The team also hosts experts in applied fields (*e.g.* S. Gentric from the company Idemia in Biometrics, Professor D. Ernst from Liège University in Reinforcement Learning Applied to Energy Markets).

An ongoing commitment to continuing education. The team has created and coordinated the specialized masters ‘Big Data’ and ‘Artificial Intelligence’ (about 50 students per year), in addition to the certificates ‘Data Scientist’ and ‘Artificial Intelligence’ and has designed/implemented many popular short continued education programs for Télécom Executive Education, in the fields of AI, Data Science and Audio Signal Processing in particular. Given their technological impact and the related value creation, today more than ever, these fields are the subject of great interest from various companies and public institutions. As a result, the team believes its role is to participate in the continued training of industrial experts and executives. In return, this activity brings the team into close contact with the industrial sector and certain public services (*e.g.* security), which also benefits its research. Over the period, Professors S. Cléménçon, F. d’Alché and P. Mozharovskiy have also designed and produced an online introductory course in Machine Learning addressed to professionals and financed by Institut Mines Télécom.

17.4.2 Research valorization and transfer

The team also participates in valorization and transfer activities. In 2018, the rights of patents on machine-learning-based scoring technologies developed by S. Cléménçon were transferred to the company Aleia. In 2023, the Prématuration project ARTIST led by S. Cléménçon aiming to valorize new technologies for handling selection bias and fairness constraints in AI was funded by IP Paris and is finding a market in the banking/insurance sector, in particular, thanks to the company AI-vidence. In 2018, the AHEAD (Augmented HEADphone Experience) project, coordinated by S. Essid, was selected by SATT Paris Saclay, and technology transfer was initiated to the startup company The-A-sense. The project aimed to develop an intelligent headphones system and distributed audio recording infrastructure to offer sports events spectators an immersive audio experience of the game. It was stopped during the Covid-19 crisis. In 2022, S²A joined the Audible project (PI: S. Essid) supported by a BPI i-démo grant⁴ to contribute to the development of AI

⁴<https://shorturl.at/R1Asa>

at the edge solutions targeting hearable technologies (especially TWS/earbuds). Specifically, our team is seeking to develop extremely efficient real-time machine listening, speech processing, and MIR solutions that can run on very low-consumption hardware.

The research activity of the S²A team is essentially methodological and the vast majority of its scientific production consists of highly specialized scientific articles. However, to increase its impact and disseminate its results beyond the academic community, the team is committed to meeting the highest standards of reproducible research. In particular, each publication is now accompanied by open-source code and demos, usable for research and development companies. With this in mind, more ambitious software and platforms have also been elaborated. Noticeably, the chair DSAIDIS allowed us to share our results with industrial partners and to offer them a presentation of the state-of-the-art in various topics.

17.4.3 Science popularization

The mere mention of AI usually produces ambivalent reactions. This is frequently informed by commonly held fears usually aroused by real dangers such as the automation of decision-making processes along with a loss of control, the negative impact on employment, the dependence on information systems, and the loss of privacy. That said, there is also evidence of enthusiasm for what could be accomplished in science, medicine, commerce, transportation, communications, and security by combining the masses of data now available with the thriving information sciences, in particular in the field of machine learning. Although it is still difficult to define how best to organize efficient regulations without hampering the promised advances, controlling risks entails, among other things, education and training via wider dissemination of a "culture of data and algorithms". The team actively participates in educational initiatives of this kind and has shed light on societal issues raised by AI (*e.g.* fair face recognition systems, explainable or frugal AI). Several members of the team have written various popularization reports and papers, in media such as *The Conversation*, or for think tanks such as the Institut Montaigne. Professor F. d'Alché has participated in the editorial board of *Polytechnique Insights* over the period, Professor C. Clavel, as well as other researchers, have contributed to several radio broadcasts (*e.g.* *France Culture*⁵). Professor G. Peeters and S. Cléménçon have taken part in the Netexplo "DeepTech for Business" program, receiving a Trophées du Digital Learning award in 2022.

Beyond the hot topics of the moment, the team (through Professor G. Richard) has also contributed to the museum *Maison Poincaré*, dedicated to the popularization of mathematics (inaugurated in September 2023), while S. Cléménçon took part in the organization of events such as 'Maths en Jeans', as well as those organized by the *Salon Culture & Jeux Mathématiques*.

17.4.4 Synthetic self-assessment

Opportunities: The interaction of the team with Society is greatly facilitated by the fact that AI is now under the scrutiny of the public and some of its topics are in the spotlight (*e.g.* trustworthy, explainable and ethical machine learning in the forthcoming era of the AI act)

Strengths: The team's connections with industry and its understanding of the issues at stake concerning applications is a valuable asset when communicating with certain actors in society as well as for continued/doctoral education programs.

Weaknesses: The administrative red tape, the lengthy legal argumentation (regarding intellectual property especially) the lack of support, in the field of scientific communication in particular, are the main obstacles to more effective interactions.

Threat. Society's versatility when it comes to AI and a pure technology-based vision of the field in the age of ChatGPT could compromise the visibility of S²A's research activity.

⁵<https://www.telecom-paris.fr/chatgpt-nouveaux-enjeux-ia-chloe-clavel-franceculture>

Part III

UNIT TRAJECTORY

Chapter 18

Trajectory of the LTCI

This chapter reviews the laboratory project and its organization. It analyzes its strengths and weaknesses and presents the trajectory of the laboratory for the coming period, on the scientific and organizational levels.

18.1 Research dynamics and ambition

History of the unit

As shown in section 1.2.1, the LTCI was created in 1982 by Télécom Paris (ENST at that time) and CNRS as ERA, then passed to URA CNRS in 1994 and finally to UMR CNRS in 2003. In 2008, the ENST umbrella became Télécom ParisTech, and in 2019 changed back to Télécom Paris and, the same year, joined the newly created Institut Polytechnique de Paris (IP Paris). In 2016 the CNRS changed the status of the LTCI from UMR to that of FRE and then withdrew from the unit the following year, therefore from January 1, 2017. 24 CNRS researchers and one administrative officer then left the LTCI which is currently under the sole supervision of Télécom Paris, one of the schools of Institut Mines-Télécom (IMT).

Scientific positioning

The LTCI is characterized by its broad coverage of the field of information and communication science and technology. Its research activities range from the hardware layer (electronics, optoelectronics, system on chip, antennae, microwaves . . .) to the software layer (systems, algorithms, protocols . . .), and applied mathematics (graph theory, optimization, probabilities, statistics . . .). These activities encompass studies on different kinds of data (audio, video, images, semi-structured data, and text) as well as works on network performance and services, or quantum information and cryptography.

Ambition

The ambition of the LTCI is to continue to be a flagship laboratory in computer and communication sciences, with international scientific influence, solid links with the socio-economic world, and a strong commitment to training.

Project organization

As indicated in sections 1.2.2 and 1.2.5, the laboratory project is organized in a matrix manner, with three departments (15 teams, each carrying a scientific project, grouped into 3 departments) and six transversal thematic axes. The thematic axes are in line with current scientific issues and future challenges in the computer and communication sciences. They are intended to strengthen

the cohesion of the laboratory and constitute a vector for integrating the laboratory into the Institut Polytechnique de Paris and, more broadly, into the scientific environment of the Orsay-Palaiseau-Saclay area.

Self-assessment

Strengths. The unit has scientific production which remains at a very high level over the years, on both quality and quantity. It has a very strong involvement in research and visibility in particular in Europe with three ERCs in progress (one starting, one consolidator, and one advanced), 5 in total since the launch of the program. The prestigious awards obtained by the members of the laboratory (Grand Prix IMT-Académie des Sciences, Optica Fellow, IEEE Fellow, George Boole Prize, Prix Gallien, Prix Science Ouverte, Prix Joseph Fourier, etc.), the multitude of best thesis and best paper prizes, as well as the participation of the LTCI members in numerous editorial committees of journals and conferences, and their participation in the organization of flagship conferences, show the international influence of the unit.

The LTCI's scientific production is of excellent quality, with publications in the best journals and conferences in the fields covered by its teams (such as IEEE, SIAM, Light Science & Applications, and ACM journals and conferences), with numerous regular publications in highly selective conferences such as Neurips, ICML, AAAI, IJCAI, ICCV, INFOCOM, Crypto, Asiacrypt, The Web Conference, BigData, SIGCHI, SIGGRAPH, etc. (see Chapter 2 and the teams' self-assessment chapters).

The LTCI's interaction with the socio-economic environment is of a high level. The unit benefits from Télécom Paris' membership of the Institut Carnot Télécom & Société Numérique. It has several industrial chairs, several joint laboratories, and numerous Cifre contracts with industrial companies such as EDF, IDEMIA, Veolia, Thales, Nokia Bell Labs, etc. Valorization and transfer are also at a very high level with many prematuration and maturation projects and numerous patents. Three spin-offs were created during the period.

The LTCI also has a strong commitment to open science and the promotion of open development practices in the field of computer science (see the COSI¹) and a good commitment to science popularization and scientific mediation.

The number, diversity and quality of the platforms should also be highlighted. The unit participates in the development of a very large number of software platforms, some with international visibility, such as GPAC, River, Software Heritage, scikit-network, or YAGO. The latter earned the "2022 French Open Science Prize for Research Data".

After the disengagement of CNRS at the beginning of 2017, which led to the departure of 24 researchers from different teams, the unit had to do significant work on the scientific positioning of the teams around a common scientific project. This positioning work led to the restructuring of certain teams and the strengthening of other weakened teams, through recruitments and redeployment of positions.

The unit has shown great resilience in front of these significant structural changes, also since its close environment has evolved significantly with the move to Palaiseau and the creation of the Institut Polytechnique de Paris in 2019. The LTCI has demonstrated great stability and adaptability.

Several members of the unit teach in the most renowned master's degrees, like MVA (Mathématiques, Vision, Apprentissage) co-directed by a member of the IMAGES team, or the MPRI (Master Parisien de Recherche en Informatique). Also, several members of the unit have responsibilities in master's degrees at IP Paris, or at the doctoral schools (Ecole Doctorale de Mathématique

¹<https://www.telecom-paris.fr/en/research/labs/information-processing-ltci/open-software-innovation>

Hadamard and Ecole Doctorale de l'Institut Polytechnique de Paris).

Threats. The multitude of platforms and their high level of technicality undoubtedly require additional efforts to attract and retain the skills necessary for their development and maintenance.

For part of the teams, not being able to host full-time researchers constitutes a risk to their fundamental research activity with potential consequences on the rest of their work and their potential for innovation and transfer.

Opportunities. The fact that the unit has recognized expertise in very dynamic research domains, with high expectations in terms of socio-economic benefits (AI, networks of the future, digital trust, quantum computing, etc.) enables it to benefit from important funding put on these subjects by the authorities (France 2030 program) and the private sector, via bilateral collaboration, industrial chairs, and the IP Paris's interdisciplinary centers.

Another major opportunity is the dynamic created with the launch of the Institut Polytechnique de Paris, which brings together a fairly large community (around 300 permanent faculty) in the domain of computer and communication sciences. There are more and more interactions between researchers from different laboratories, in terms of teaching, supervision of PhD students, or proposals to calls for projects. Several teams have the opportunity to develop more easily and gain in attractiveness, benefiting from complementary internal expertise and the visibility and attractiveness of the Institut Polytechnique de Paris, which will continue to grow.

18.1.1 Teams research dynamics and ambition

ACES. The ACES team covers a wide range of issues related to digital trust, which encompasses secure distributed algorithms designed to withstand coordinated attacks, resilience in customer-facing systems, reliable scheduling algorithms for critical embedded systems amid uncertainties, resilient design, and development strategies for complex and autonomous systems, as well as ensuring trust within the software supply chain. These topics are currently of great interest due to the increasing reliance of all societal aspects on digital processes. Moreover, as cyber-physical systems are still in their infancy, guaranteeing the correct functioning of systems that increasingly influence the physical world is becoming ever more crucial.

Additionally, the team is progressively integrating considerations of consumption and energy factors into its research agendas. For example, it is necessary to create new algorithms that are compatible with intermittent renewable energy sources, without sacrificing the reliability of critical systems. Utilizing on-device learning on smaller gadgets can decrease energy and infrastructure dependencies while improving privacy by processing sensitive data locally. Developing new distributed algorithms, secure protocols, and software engineering methodologies and processes are essential to detect and counter-attack, regardless of whether they come from nation-states or independent, possibly coordinated, adversaries.

C2. We continue to develop excellent research in all three domains and their interactions: cryptography, cybersecurity, and fundamental research.

Cryptography: Our research projects aim to introduce new tools and techniques to tackle cryptographic questions arising from new technologies such as cloud services, IoT, or big data, and against strong adversaries. The following directions will be developed:

- Advanced Cryptographic Primitives to enhance privacy (by reducing the need for trust in authorities, e.g., cloud servers): The objective is to decentralize computations in protocols that process data supplied by multiple distrustful parties, to meet the security and privacy requirements brought about by emerging applications. We aim to provide new insights into

future platforms and how to protect sensitive data and individuals' privacy in such situations, introducing new concepts and paradigms as we did with anamorphic cryptography.

- Algorithmic tools for advanced post-quantum cryptographic primitives: This direction will be mainly developed to introduce algorithmic problems and investigate their hardness for designing concrete primitives.
- Quantum computation: We work on the new possibility of realizing primitives that cannot be done with the classical model of computation. Recently, we proposed a new method for quantum key leasing and we introduced a new primitive of zero-knowledge proof of quantumness. This direction is very open and could lead to fruitful collaboration with other teams working on quantum information.
- Symmetric cryptography: The aim is to design lightweight cryptography and combine it with algebraic tools in asymmetric cryptography to design efficient algorithms for zero-knowledge proofs and threshold cryptography.

Cryptography is a central theme in our research activities. We expect to see a great deal of synergy between our research topics in cryptography on the one hand, and cryptography and cybersecurity or fundamental research on the other. More specifically, the question of designing quantum-safe solutions for advanced primitives and for symmetric cryptography will be central in our work. In addition, we also plan to work on the way cybersecurity tools could work in the case where the input data is encrypted (e.g. for encrypted traffic or protected thanks to encryption by the data owner). Lastly, the fundamental work on mathematics lies at the heart of the foundations of cryptology, so the link is done quite naturally.

Cybersecurity: To address the vast and disparate group of interconnected networks and devices, it is necessary to implement tailored security and confidentiality systems, where underlying mechanisms are closely related to the services involved. Security requirements may vary considerably depending on the services offered.

We work on tailored approaches to security that can meet the broad range of security requirements and provide adaptive security systems. Those address multiple operational and environmental constraints while taking into account the following properties: flexibility, lightness, autonomy, mobility, and interoperability.

Aiming to defend against a high number of critical attacks, the challenges that we address are: adaptive end-to-end security architectures with lightweight and scalable security functions and protocols, scalable trust management with lightweight cryptographic functions/mechanisms and crypto-agility, identity management and lightweight authentication mechanisms, blockchain-based solutions for cybersecurity mainly for access control, integrity and resilience. These application fields can be found in several collaborative research activities split into three topics: security and trust in information and networking systems, attack analysis, and misbehavior detection and privacy.

Our future research projects mainly strengthen the above activities with new domains such as privacy models, Blockchains, and protocols for time-sensitive Networks (TSN), in particular:

- Trusted and secure communications in scalable and constrained environments.
- Security data analytics in large-scale networks/systems.
- Attack Analysis and Countermeasure in Information Network.

Fundamental research: We traditionally conduct research activities in fundamental mathematics—algebraic geometry, number theory, combinatorial coding theory—and in areas at the frontier between discrete mathematics and computer science—automata, coding theory, cryptography, and computational complexity—but still with a predominantly mathematical perspective. We will continue to develop these activities, which are foundations for applications, cryptography in particular.

C2S. The context of microelectronics is evolving rapidly: strong growth in the semiconductor industry identified as an element of sovereignty in Europe, the development of 6G communications, the need to significantly reduce the electrical consumption of systems beyond technological shrinkage, and the explosion of AI in all areas of application. In this context, our research themes are evolving to focus on the most crucial subjects while taking advantage of our skills.

In the short and mid-term perspectives, we will face a multitude of additional technical challenges and therefore opportunities to innovate. Thus, we observe i) the complexity of communication systems with the multiplication of bands and standards as well as intensive use of techniques such as Massive MIMO and Beam Forming, ii) increased tension on the use of batteries with IoT and electric cars, and iii) a more complex operation of transistors requiring increased mixing between digital, analog and RF as well as revisiting design approaches.

- **Innovative communication systems.** We are working on building highly digital transmitters for 5G/6G with massive MIMO. The specificity of our approach is to co-design the different parts of the chain including the digital pre-distortion, the data modulator, the digital-to-analog converter, the RF parts as well as the DPD feedback chain. This enables a more efficient design and power-efficient design. Our objective is to design in collaboration with industrial and academic partners this kind of architecture in advanced CMOS nodes. We are also considering the use of artificial intelligence to improve the performance of analog and mixed-signal systems. Actually, using a neural network as a pre-coder is a promising approach to correcting the imperfections of communication systems.
- **Ultra-low power systems.** Another topic that we are targeting is very low power consumption systems. We are addressing this topic from 4 different angles. The first is to co-design the protocol level with the physical level. We are more specifically working on the design of a very energy-efficient wake-up radio that takes profit from IoT protocol specificities. The second angle is ultra-low power design. Our objective is to propose solutions that achieve very low power consumption by using innovative solutions at the architecture level and transistor level. The third angle is integrating optimized energy harvesting approaches. Several approaches are considered such as adapting the emitting devices' waveform to energy harvesting purposes, and using beamforming is also promising for such applications. The last angle is developing a new acquisition scheme (Analog to Feature) that is aimed at reducing the amount of data to be transmitted in continuous IoT scenarios while minimizing the power consumption of the sensor and maximizing performance.
- **AI for AMS-IC design.** The design of Analog Mixed Signal (AMS) Integrated Circuits (IC) is not an easy task. There are difficulties all along the design process. Given the required specifications the designer must first choose an adequate architecture which requires knowledge and experience. The large number of parameters of a given architecture must then be tuned. Tuning these parameters often relies on human experts and their intuition because the relationship between parameters and performance is subtle and uncertain. Optimal tuning requires many simulations which can be very slow for complex circuits. Optimizing both the architecture and the parameters is thus a very complex and time-consuming task. This could be even worse by taking the layout process into account. Our objective is to work towards finding new methods that outperform existing ones. Such a method should focus on reinforcement learning while leveraging aspects not yet tackled such as working with multiple technology nodes, considering PVT variation, or considering layout parasitics.

ComNum. The ComNum team has developed extensive knowledge and expertise in fundamental limits and associated coding techniques for the transmission, storage, and processing of information on networks, in centralized or distributed contexts.

The team aims to continue building on this expertise for all types of communication - wireless, wired, and optical - and for all types of processing - retrieving, guessing, estimating, and detecting events. It will be important to take into account timely and stringent constraints such as

complexity, reliability, energy efficiency, latency or secrecy.

In the next five years, the team intends to address the following scientific challenges:

- Distributed sensing: Crucial for 6G and beyond mobile standards that are expected to provide anytime and anywhere sensing capabilities to all terminals in the network,
- Optical satellite communications: High capacity optical earth-satellite links are foreseen to connect the terrestrial network to the space segment in 6G and beyond,
- Distributed processing using Refractive Intelligent Surfaces (RIS): One of the most promising technologies to maintain high spectral efficiency performance for single- and multi-user configurations,
- Universal information measures: Necessary for any computer science problem that can be modeled by an information flow system with a specific task and criterion (e.g., distortion, guessing, estimation, etc),
- Data compression and prediction: To manipulate data locally in a space- and time-efficient manner,
- Interpretable Machine Learning: Obtain insight into the limitations and guarantees of machine learning algorithms using suitable information measures,
- Information leakage in protected cryptographic implementations: Universal bounds for any attacker to ensure a minimum number of traces to achieve a given success rate or guessing work.

Shortly, the team plans to choose another name to better reflect its current research topics.

DIG. The research activity of the DIG team covers data management, knowledge representation, logic, graph mining, machine learning and AI. This combination of techniques and skills is essential to address the issues raised by the advent of generative AIs, both from scientific and societal points of view. The results of generative AIs are unpredictable and probabilistic by nature, most often true or plausible but sometimes wrong or incoherent. It is a challenge to enforce common sense and logic, as most generative AIs rely on a black-box architecture. The team will develop new approaches combining symbolic methods and neural methods to address this challenge. Specifically, the team will focus on the following topics, in addition to its long-term research activity on data, knowledge and graphs:

- Knowledge-based AI. The objective is to connect AI to knowledge explicitly, rather than implicitly as today. The link between knowledge and decision should be known and controllable, rather than loose and inferable.
- Domain-specific AI. The application of AI to specific domains like law or medicine is far from obvious. There is a need to encode data, knowledge, and logic to make AI applicable and trustworthy. The team will rely on its current skills, especially in the field of legal AI, to propose new approaches and solutions for real-world problems.

DIVA. The DIVA team continues to focus on fundamental and applied research in human-computer interaction and information visualization. Its research follows a transdisciplinary approach across computer science, design, and the social sciences focused on the computer as a tool through which people interact with their digital world.

The main high-level themes of the team continue to be organized around two main axes: Novel interactions to enable and build the user interfaces of tomorrow, and Homo numericus, which is focused on people's relations to these technologies.

The specific topic applications within these areas continue to evolve. For example, the team has expanded on its work in large- and small-scale information environments and cross-device

interaction into immersive mixed-reality environments. It continues to investigate malleable and collaborative software environments for novices and experts. Work on these areas will continue to expand through the next evaluation period.

Moreover, AI technologies continue enabling new types of interaction and tensions between people and the computational tools they use. We expect that the team will continue to develop its work in AI-assisted interactions that keep that user in control of their technology.

GTO. GTO has been and remains dedicated to advancing the frontier of optical communication devices, systems, and networks. With a strong foundation in optical transmission technologies, the group is well-positioned to explore new horizons in quantum technologies, free space communications, and sensing. Our research aims to leverage quantum phenomena for secure and energy-efficient communication as well as new applications, push the boundaries of traditional free space optical links for enhanced data rates and reliability, and develop novel optical sensing techniques for diverse applications ranging from enhancing network operation to environmental monitoring. By embracing these emerging areas, our group seeks to drive innovation at the intersection of optics, quantum mechanics, communication and information theory, contributing to transformative advancements in information technology and beyond.

IMAGES. The IMAGES team has developed its expertise on a wide spectrum of topics for the restoration, synthesis, analysis, and understanding of images, volumes, and videos. Over the period covered by this report, the activity has mostly shifted toward deep learning-based methods, balanced between applicative and methodological contributions. The team has an original positioning at the interface between imaging sciences (from image acquisition to the specificities of the different fields of application) and mathematical modeling. In the forthcoming years, one of the main challenges will be to develop deep learning approaches with better interpretability and better understood inner mechanisms. A second principal research direction is concerned with efficient learning strategies that can deal with scarce, poorly annotated, or small databases, a common concern to most applicative fields of the team.

In the field of medical imaging, we will keep on focusing on new learning approaches (self-supervised approaches, representation learning) and mathematical models for image analysis and understanding which answer specific needs and constraints of medical data, such as low-data regime, efficiency, data biases, privacy and robustness. Another emerging activity is multimodal analysis (different image modalities, multi-omic, time series, e.g. for functional data, text, etc.). Besides, the team will keep and develop its strong expertise in image reconstruction and inverse problems. Last, we will of course maintain our numerous clinical collaborations (NeuroSpin, Pasteur Institute, St Joseph hospital, etc.) and extend them, in particular toward the new Paris-Saclay hospital and with local partners at IPParis such as LOB, LOA, LadHyX laboratories. These partners work on new high-potential imaging systems for which there is a need for new AI methods for image analysis.

For remote sensing activities, the main challenges we are facing are the development of auto-supervised or weakly supervised methods and the joint use of multi-modalities combining optical, hyperspectral or radar data. The domain is also driven by the new sensors that have been recently launched or will be launched in the next few years whether they are from space agencies (SWOT, BIOMASS, EnMAP) or private companies (Iceye,...). These new sensors and constellations open the door to new applications, especially on environmental issues. Fruitful methodological perspectives include auto-supervised approaches for image restoration and change detection, representation learning for multi-modality combinations, and introducing physical and geometric knowledge of the acquisition systems. Another area of research will focus on the design of deep networks for inverse problems by deploying algorithms (deep unrolling). By creating a link between iterative optimization algorithms and neural networks, the resulting architectures benefit from strong interpretability, while requiring little training data and low calculation times. The applications envisaged relate particularly to hyperspectral imaging (unmixing and super-resolution),

SAR imaging (tomography) and astrophysics (deconvolution of large-scale data).

The research of our team in computer graphics is grounded on the versatility of methodologies with particular attention to visual applications. This nature develops a unique perspective to our research, which focuses on physics-based and data-driven simulations as well as sketch-based image and geometry manipulations. These subjects stand up as crucial elements for digital content creation and can connect to different disciplines, for example, mechanics to reproduce natural phenomena such as fluid and soft material dynamics, and arts to provide creative tools. Not only do we bridge the gap between scientific/engineering and visual applications, but we also branch out into a direction for visually oriented methods that aim for better aesthetic outcomes.

A consequent effort has been devoted to the development and understanding of generative methods for the restoration, enhancement, editing, and synthesis of images and videos. The first major challenge in this direction is that the most recent architectures involve massive network sizes that are not only prohibitive but also unreasonable from an environmental aspect. Developing lightweight approaches, be it through specific training modalities or dedicated architectures, in particular for diffusion models, is therefore of great interest. A second subject of interest is the understanding and possibly the structuring of latent spaces of generative models. Eventually, we believe that recent progress in the mathematical modeling of generative approaches opens exciting new research directions. Unrolling methods have already been mentioned as open perspectives in terms of interpretability and light training. Another research avenue is plug-and-play methods, whose study can provide theoretical tools for analyzing the convergence of restoration algorithms based on new priors related to diffusion models. In addition, the use of Bayesian methods could yield uncertainty bounds, that are crucial in sensitive applications in remote sensing or medical imaging.

LabSoC. The main research focus of LabSoC involves the modeling and verification of critical embedded systems, encompassing efforts towards more suitable models that address the emerging challenges of these systems, and verification techniques that are better equipped to verify new properties (such as security) while accommodating the increasing complexity and growing heterogeneity of these systems. Within the design phase of embedded systems, the team will also continue to focus on the design of space exploration.

From a modeling point of view, we intend to address the following scientific challenges:

- **AI-assisted Cybersecurity.** Our focus is on handling cybersecurity threats within safety-critical systems, during the design space exploration of (critical) embedded systems. Historically, the approach involved compartmentalizing efforts—dedicating separate silos to safety and cybersecurity before integrating the outcomes. Currently, we are exploring a more integrated approach, employing AI to concurrently address safety and cybersecurity. This method involves the AI-assisted selection of safety and security mechanisms that not only complement each other but also ensure that other system properties are not adversely affected. More generally, we have already started to investigate (best paper award at Modelsward’2024) how LLMs can be used to assist engineers in modeling complex systems.
- **Support for new architectures in our modeling and verification approaches:** The integration of AI modules into embedded systems is a recent trend. AI modules can, e.g., handle intrusion detection, object identification, and autonomous driving decision-making. However, navigating the design space of systems that incorporate AI mechanisms remains an open challenge, particularly in the realms of modeling and verification, where safety, security, and performance are at stake. Our approach will begin with the smart abstraction of these AI modules, coupled with the creation of libraries of abstract components to represent them, accounting for their potential safety and security implications. Subsequently, we aim to develop methodologies that incorporate these modules into the verification process, leveraging the abstractions established in the initial phase.

From a verification perspective, a few challenges that the team will tackle in the coming years.

- **Incremental verification.** Verification is traditionally resource-intensive. However, the shift towards agile development methodologies induces more frequent system verifications. Likewise, system updates, particularly after the discovery of vulnerabilities, require modifications and subsequent re-verification. To address this, we are pioneering methods with incremental verification, aiming to reduce the verification complexity by reusing verification results at stage $n - 1$ at stage n . Our preliminary findings, particularly with simple properties, are promising. Moving forward, we plan to extend these methods to more complex attributes, encompassing safety and security properties.
- **Correct-by-construction.** Correct-by-construction commonly refers to the B method where each increment is proved to conserve an invariant. Since our interest lies in general-purpose modeling languages, whose formality is backed with automaton, we intend to further define formal refinement processes ensuring safety, and also security processes, based on automata-refinement.

Regarding application domains, our focus remains broad and adaptable, targeting any area where development methods necessitate modeling and verification, particularly those grappling with the outlined challenges like cybersecurity/safety, AI integration, formal refinement, and incrementality. Our scope encompasses a diverse range of sectors, including but not limited to transportation systems (such as automotive), industrial systems (aligned with 'Industry 4.0' paradigms), telecommunication systems (illustrated by our involvement in PEPR5G), and smart cities (as demonstrated by our recent ANR project MoVe4SPS).

Our platforms will persist in effectively showcasing the practical applications of our scientific outcomes. We will ensure they are updated consistently in alignment with these outcomes.

RFM². The RFM² team is aiming to push further its current trajectory, particularly in terms of frequency rise, to contribute to innovations beyond 5G and towards 6G, while focusing its efforts on two major challenges. The first is the efficient use of energy resources, involving the optimization of components and subsystems to minimize losses, and the implementation of means to harvest them when possible. The second is more precise knowledge of people's exposure, especially in a context where multi-antenna systems are growing, using statistical models and artificial intelligence tools.

More specifically, on the first axis, the design of multifunction antennas, intended to be low-profile, multi-band up to millimeter wave frequencies, and reconfigurable with a limited number of active components is a key challenge. Moreover, the design of efficient metamaterial absorbers for energy harvesting systems and rectennas up to millimeter wave frequencies, along with the joint design of the components will enable us to greatly reduce energy consumption and electromagnetic pollution in an environment of generalized communications.

Our activities in the design and/or characterization of circuits and millimeter power transistors should allow us to have access to the III-V Lab technology (i.e GaN process design kits) to extend our research to the design of GaN MMIC amplifiers (LNA and PA for 5/6 G telecommunications systems in the Ka-band (26.5 - 40 GHz) and beyond (massive MIMO systems)). The objective is to obtain a strong integration associated with the best possible energy efficiency.

Concerning modeling, efforts will be pursued and developed, in particular on stochastic surrogate models of MIMO antennas subject to randomness (tolerances, nearby environment - including user's influence on terminals -, aging, etc.). The robustness of precise indoor localization techniques based on UWB signals will also be improved.

On the second axis, taking into account the public concern about 5G and probably about future 6G networks, the team intends to develop its activities toward EMF exposure mapping using surrogate models based on statistical models as well as artificial intelligence (AI) tools. Within the context of 6G, multi-antenna systems and mm-waves, the team plans to assess, on one hand, the uncertainties linked to AI forecast and EMF mapping and, on the other hand, to build tools and indicators that will be used to build EMF aware networks.

RMS. In the next period, our activities will be driven by the various structuring national and local programs: PEPR "réseaux du futur", France 6G program, Negedi (IPP), etc. Through our research in machine learning and energy saving for cloud services, our platforms for IoT and 5G/6G systems, and our capacity to analyze the performance of protocols and systems with mathematical models, we are at the heart of these initiatives. We intend to continue developing our activities in these fields by local recruitments and by federating other researchers working on close subjects.

We also have promising perspectives on the applications of networking technology to agriculture 4.0 which will create new opportunities for research on IoT, wireless systems, etc.

S²A. From a long-term perspective, the expertise of the team S²A lies in the fields of applied mathematics and computer science and combines several academic disciplines: probabilistic modeling, statistics, optimization, signal processing, machine learning, and natural language processing. Its research consists in the development of algorithms to analyze data, their mathematical analysis (theoretical guarantees), and their applications to specific domains, audio signals, and multi-modal data. The ever-increasing variety of the data (w.r.t., e.g., their nature, volume, dimensionality, complexity, sampling rate, incompleteness, exposure to bias/truncation/contamination/noise) collected by constantly developing sensor technologies (e.g. mass spectrometry, IoT, satellites, spatial telescopes) and that of the objectives/constraints of modern data analysis (e.g. prediction, explainability, simulation, scalability, robustness) are inexhaustible sources of methodological problems and will undoubtedly continue to be a driving force for the team's research activity, as it has been since its creation. In its composition, the team has succeeded in preserving the means of interdisciplinarity that constitutes its originality and an asset for the development of high-impact results. With the recent disappearance of expertise in the analysis of human-machine social interactions (inherent in the departure of leading researchers in this field) and the reinforcement of its knowledge in Natural Language Processing, the team's themes will focus on three axes, involving each the various disciplinary skills of the team.

- **Mathematical Foundations of AI:** Because the tasks entrusted to AI must be based on algorithmic techniques that are not only efficient but also well understood theoretically from a mathematical perspective, the team is committed to developing methods that meet many of the challenges on the increasingly demanding machine-learning agenda (e.g. robustness, scalability, privacy-preserving, fairness, explainability, weak-signals, structured and high-dimensional data, active learning), as well as a dedicated validity framework for the latter.
- **Audio Data Analysis and Signal Processing:** The team's original position, well balanced between methods, models, and application to speech and audio processing problems being of its main strengths, will be reinforced while establishing some new lines of major interest. We will further develop our work on generative models (especially around diffusion models, and adversarial networks), on representation learning (discrete neural representation, unsupervised learning, ...), and on hybrid models in jointly exploiting data-driven and model-driven models as a path towards more explainable and frugal AI models. Beyond our current applications portfolio in speech and music processing, a new axis on Extended Audio Reality (EAR), a domain that encompasses Augmented, Mixed and Virtual Reality, will be developed.
- **Multimodal AI:** With the rapid development of generative AI, there is a huge surge of interest in large, versatile models that may be able to execute tasks from instructions, without any specific training or supervision. Current models however have many weaknesses, and as they are often linked to natural language itself, tackling them requires looking at both appropriate machine learning methods and insights from computational linguistics. We intend to develop our work on analyzing and mitigating those weaknesses while continuing our previous research directions on dialog, as recent generative models are interactional by nature. To be applied to more diverse and structured data and to be truly versatile, these models will also require to be multi-modal, and this is becoming a more and more popular research direction. We hence intend to bring together those expertise, through close collaborations with other teams, especially with the MM team. This is further motivated by the convergence of the methodologies of our respective fields.

In the shorter term, the team's scientific positioning around certain methodological issues raised by AI, which has made its success in recent years, remains relevant but needs to be clarified in the era of ChatGPT.

Responsible and trustworthy AI. A major challenge for the team will be to understand that the controlled progress of AI is not just a question of technological resources (which only certain high-tech companies have) but will also depend decisively on the answers to certain methodological problems (academic) research can bring. The team is well-placed to take over the topics of trustworthy AI. There are still many scientific challenges to be met, from the complexity of the information that can be fed into AI, to the difficulty of the tasks that we want to delegate (at least in part) to intelligent, autonomous systems in the future of course. In many cases, the level of delegation granted to these systems will depend to a large extent on solutions to the issues of ethics (i.e. processing of personal data while respecting privacy, fairness) and reliability. This brings us back to the development of statistical learning techniques that hold up even if part of the data has been "contaminated" (for example due to biases in measurements or the deliberate intention to impair the operation of the automated system). Not only must they hold up under such circumstances, but they must also yield decisions that end users (human beings) can interpret/understand. Energy frugality is also key to making AI acceptable. These questions are likely to lead us to revisit AI algorithms in depth, assessed no longer through simple predictive performance, but in the light of a diversity of criteria, requiring us to find satisfactory compromises/balances. These are the keys to a regulated AI that does not stifle innovation. In particular, the following topics will form a significant part of our research program: AI explainability; Energy-efficient AI; Privacy-friendly AI, confidentiality; Trusted, certified/standardized AI.

These topics can be possibly tackled at a high level but also offer a wide variety of scientific problems depending on the domain considered (e.g. audio data analysis and signal processing, natural language processing) or the application under study (e.g. biometrics). The team's methodological skills and expertise in certain fields, combined with its collaboration with industrial partners, can enable it to achieve high-impact results.

SSH. The SSH team's research activities for the next five years will encompass various areas of electronics and embedded systems, closely aligned with our core competencies in design and analysis, as well as related challenges such as complexity, power consumption, safety, and security. Part of our work will integrate artificial intelligence as a tool (AI for design and analysis) or as an application (circuits and systems for AI). As such, through strategic collaborations with industry leaders, as well as national and international academic partners, we intend to develop the following topics: Safety and security of embedded systems; Micro-architecture security; Radiation resilience in embedded sensor networks; Integrated electronics for pervasive intelligence; AI-driven design of ultra-low power circuits; AI for Electronic Design Automation (EDA); Computer architecture for AI.

18.2 Organisation and development strategy

Structure and governance of the unit

The LTCI organization is structured and intertwined with that of Télécom Paris. Thus, the director of the LTCI is also the dean of research at Télécom Paris, and the three heads of the departments composing the LTCI have also managerial and hierarchical responsibilities at the level of their departments, as well as responsibility for organizing teaching. This is an asset for the unit which allows it to benefit from the structure of Télécom Paris and its resources (shared services) for the proper functioning of the unit. But, on the other hand, this may constitute an obstacle to any change in the structure or the management of the unit (management of funding, or pooling at a level larger than a department, for instance).

A significant amount of work has been carried out over the past period to improve coordination between the unit and the departments. Since the beginning of 2023, a weekly meeting has been held between the unit director and the department heads. This meeting provides an opportunity to exchange information and coordinate actions.

Possible reorganization within IP Paris

Discussions are underway within IP Paris to define the institute’s research strategy for the coming years. At the same time, a task force has been created (led by Florence Tupin from the LTCI and Samuel Mimram from the LIX) to analyse the current situation and make recommendations for a possible reorganizing of the research units active in the field of Computer and Communication Sciences. The aim is to avoid unnecessary internal competition, strengthen internal interactions and the overall dynamics of the scientific community, and make improvements in terms of readability and visibility. The concerned units, apart from the LTCI, are LIX (Laboratoire Informatique de l’Ecole Polytechnique, UMR CNRS), SAMOVAR (Télécom SudParis), U2IS (ENSTA Paris) and joint research teams with Inria. The conclusions of this work should be known by the end of June 2024.

It is difficult at this stage to predict what choices will be made, but there is a clear desire to move towards greater coordination and integration at research level.

Resource development strategy

The laboratory has always been able to diversify its sources of funding, between national public funding, European funding and private funding (sponsorship and bilateral contracts with partner companies).

Its overall level of funding is excellent, with more than 8 million euros per year for less than 130 faculty. The aim for the next period is to maintain this balance, while considering increasing the volume of European funding. This will increase the resources that can be pooled to provide additional funding for the laboratory’s scientific project.

18.2.1 Teams organization and development strategy

Most teams have described their organization and development strategy in the chapters of the self-assessment devoted to them.

C2S. The C2S team development strategy aims at developing more collaborations within other teams. There are already a number of joint projects with S2A (O. Fercoq, P. Ciblat), RMS (M. Coupechoux), and COMNUM (A. Tchamkerten).

In terms of organization, we plan to reinforce our collaboration with SSH (L. Naviner, S. Chaudhuri). We identified that we share with them our three main research topics; we are complementary, addressing together both digital and AMS circuit design. We plan to develop our three research topics, supported by national and European research funding. Recent projects include:

- BPI France projects: Beyond 5G (since 10/21), DOCTE6G (since 04/21)
- PEPR projects: PEPR 5G et Réseaux du Futur (since 05/23)
- CIFRE contracts from ANRT: NOKIA (2 theses since 2023)
- Industrial chair: C3S (since 10/23)
- Horizon2020: SHIFT (since 12/22)
- HORIZON-EIC: PHAI-SoC (submitted)

In addition, we will benefit from the creation of the new joint laboratory with STM, due to be signed in 2024, for more collaborations in national/European projects and more CIFRE theses.

LabSoC. All permanent staff of LabSoC is over 45 years old. To maintain its activity and reinforce its dynamism, the LabSoC team needs to recruit young scientists. In addition, the recruitment of at least one research engineer to help us maintain our platforms (TTool, rover) would enable us to devote more time to fundamental research, and thus better prepare for future collaborations.

RFM². In line with our objectives on the second axis, we plan to recruit during the year 2024 a permanent researcher who will ensure the sustainability of the C2M chair and develop its activity.

S²A. The team will pursue its strategy of diversifying funding sources and maintaining its privileged relationships with industrial companies. In particular, in collaboration with some of its historical partners (Valeo, Idemia, Airbus Defence and Space), the team is implementing a new Chair *AI for Industry* (AI4I) for the next five years, widening the scientific perimeter of the previous chair "Data Science and AI for Digitalized Industry and Services" (<https://datascienceandai.wp.imt.fr>) to stimulate collaborative research on "Responsible and trustworthy AI" topics. Concurrently, the team will develop its recent joint lab in the domain of AI and sound (*Listen-Lab, a joint lab in machine listening*) as a key initiative for stimulating collaborative research with industry and for enhancing our visibility and impact in this research domain. A novel industrial chair project dedicated to *AI for Sustainability* (AI4S) is being set up. In addition to industrial collaborations and fruitful relationships with numerous other teams of Télécom Paris, S²A will continue to be strongly involved in public calls for collaborative projects (e.g. PEPR, cluster IA) and will strive to take advantage of its local environment and structuring initiatives.

SSH. During the period covered by this report, our team consisted of ten faculty members, including a senior researcher who played a crucial role in several security-related projects. This researcher recently retired. In addition, another senior faculty member will be retiring this year. On the other hand, we have just welcomed a young Assistant Professor specialized in electronics for AI, and are waiting for another one specialized in AI algorithms. Finally, other moves within LTCI are likely to generate one or two further departures of SSH team members. All these actual or forthcoming departures, although significant, have paved the way for a redefinition of our positioning, highlighting the opportunity for greater synergies and collaboration with the LabSoC and C2S teams.