Low-Power Communication through Analog-to-Feature Conversion

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Internet of Things
Internet of Things: a few numbers

By 2025:

- 152,200 IoT devices connecting to the internet per minute
- 4 to 11 trillions USD in economic value generated
- 73.1 Zettabyte ($10^{21}$ Bytes = 1 billion TB) of data generated

Source: Statista 2023

Source: [https://dataprot.net/statistics/iot-statistics/](https://dataprot.net/statistics/iot-statistics/)
Presentation summary

1. Wireless Sensor Networks
2. Analog-to-Feature Conversion
3. Application to ECG
4. Conclusion and Future Work
Wireless sensor network architecture

Example of the Body Area Sensor Network
New challenges

Security
- Data confidentiality and integrity
- Security mechanisms embedded into circuits

Interoperability
- Interferences between WSN
- Specific communication protocols

Data transfer
- Increasing amount of data and bandwidth
- Saturation of the RF spectrum

Power consumption
- Sensor working on batteries
- Energy source replacement is not always possible
Case study: electrocardiogram (ECG) signal

Cardiac arrhythmia detection
- Heart diseases responsible for 15.5% of worldwide death
- Well studied subject

ECG signal characteristics
- Continuous signal
- Cycle duration: 0.5 – 0.9 s
- Sampling frequency: 200 – 1000 Hz
- Precision: ~ 10 bits

Application
- Arrhythmia detection from [1]
- Signal is 800 10-bit samples
- 1 kHz sampling frequency
Case study: simple sensor

- **Analog-to-digital converter [2]**
  - 0.18 µm CMOS
  - 0.12 pJ/sample

- **Bluetooth Low Energy transceiver [3]**
  - 0.13 µm CMOS
  - Emitter: 14.5 mW
  - Receiver: 6.5 mW

- **Arrhythmia detection with linear classification [1]**
  - 0.13 µm CMOS
  - Post-layout simulation

Transmission require the most energy
Case study: using compression

Compress the data during acquisition: compressed sensing
- Use knowledge on signal structure (sparsity)
- Reduce the amount of data to be transmitted

Analog-to-information (A2I) converter [4]
- 0.13 µm CMOS
- Compression ratio of 4
- 14 pJ/compressed sample

Limitations
- Reconstruction Algorithm is complex
- Reconstruction error increases with the compression factor
Proposed solution

Extracts only useful features
- Relevant to some specific task
- Directly from the analog signal

Advantages
- Do not relies on signal sparsity
- Can achieve higher data reduction
- Joint optimization of chosen features and Machine Learning model training
- Generic architecture for different type of signals
Presentation summary

1. Wireless Sensor networks

2. Analog-to-Feature Conversion
   - System architecture
   - Feature selection

3. Application to ECG and Human Activity Recognition

4. Conclusion and Future Work
Reconfigurable System Architecture

- Extraction of the Non-Uniform Wavelet Sampling [5] (NUWS)-based analog domain features
- Analog-to-digital conversion
- Application-specific binary or multiclass classification
- Context detection
Non-Uniform Wavelet Sampling

NUWS: Acquire a small subset of coefficients from wavelet transform.

\[ Wf(a, b) = \int_{\mathbb{R}} f(t) \psi_{a,b}^*(t) \, dt \quad \forall t \in \mathbb{R}, \psi_{a,b}(t) = \frac{1}{\sqrt{a}} \psi \left( \frac{t - b}{a} \right) \]

where \( Wf(a, b) \) is the wavelet transform of \( f(t) \), \( \psi_{a,b}(t) \) is a scaled and shifted wavelet and \( \psi(t) \) is the mother wavelet.

✓ Provides information in time and frequency domains

✓ Provides several degrees-of-freedom

✗ Provides a huge number of possible wavelets selection (1 wavelet \( \leftrightarrow \) 1 feature)

Perform a smart features selection

Time window

Time shifting

Frequency

Temporal representation

3D wavelet transform
Feature Selection

Sequential Forward Search (SFS): successively adding the locally best feature in the set.

**SFS scale in !Number of features:**
- Use pre-selection method
- Based on Information Gain
- Reduce feature set to 100 best features

**3 types of SFS**
- Basic SFS
  - Maximize classification accuracy
- Adapted SFS
  - each extractor can extract multiple non-overlapping features
  - limits the maximum number of parallel extractors $n_{Ext_{max}}$
- Optimized SFS
  - also accounts for the energetic cost during feature extraction
  - based on estimated power consumption
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## Database presentation

<table>
<thead>
<tr>
<th>Application</th>
<th>Arrhythmia detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dataset (signals)</td>
<td>MIT-BIH Arrhythmia [6] (single channel from 48 ECG recordings of 30 min each, sampled at 360 Hz)</td>
</tr>
<tr>
<td>Classes</td>
<td>2 (normal, abnormal)</td>
</tr>
<tr>
<td>Initial feature number (Haar wavelets)</td>
<td>502</td>
</tr>
<tr>
<td>Type of learning</td>
<td>supervised learning, 70/30% proportion between training and test sets</td>
</tr>
<tr>
<td>Analysis window</td>
<td>256 samples of one annotated heartbeat segment (R-peak located at 100th sample) $\Rightarrow 0.711$ s</td>
</tr>
</tbody>
</table>
Application for ECG classification

- Adapted vs Optimized SFS
- Neural Network: feedforward with 1 hidden layer (10 neurons)

Only require 7 or 8 features from 3 extractors

Compression ratio: 53 vs 4 for compressed sensing
Energy comparison

- Acquisition and transmission of a 10s signal

A2F is a good and promising method to allow low-power communication and reduce bandwidth
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Conclusion and future work

- IoT brings new challenges with many small connected devices
- A2F as a solution to reduce power and bandwidth of smart IoT sensors
- Generic and reconfigurable architecture to perform A2F conversion

Future work

- Circuit design of the full converter  Refine selection with optimized SFS
- Chip fabrication  Physical measurement of power consumption
- Application to other applications (EEG, EMG, spectrum sensing ...
References


