Trends and challenges of low-power autonomous devices

Kyriaki Niotaki

Outline

- Growth in connected low-power devices
- Power autonomy challenge
  - *Energy Harvesting* as a potential energy source
  - *Wireless Power Transfer* as an alternative solution
- Radio Frequency design challenges
- Conclusions

Introduction

- Recent technical developments on low-power devices capable of connecting to the Internet are key elements for the emergence of the Internet of Things.
- The **Internet of Things**, or IoT, is based on a large number of interconnected devices capable of sensing environmental parameters, and communicating this information over the network.
- The milliards of the Internet of Thing devices will enable innovative services.

Practical IoT applications

- Smart cities
- Environmental monitoring
- Traffic monitoring
- Health
- Wearable devices
- Many more…

Home automation

Medical Devices

An example IoT application – Smart Buildings

- 75% of the existing building stock in the European Union are energy-inefficient
- the buildings count for 36% of CO_2 emissions

Smart buildings, by utilizing proper IoT devices, can reduce the buildings high energy consumption.

IoT devices promise:

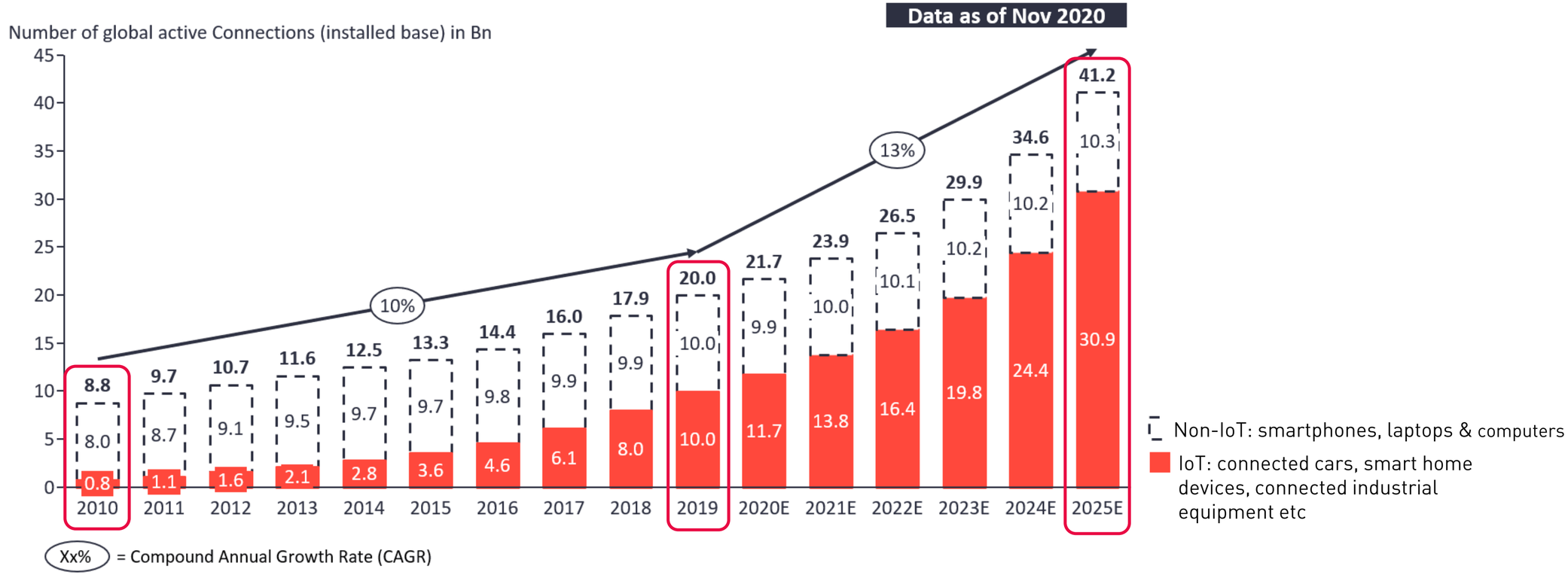
- to improve our quality of life
- to reduce carbon emissions.

https://www.eetimes.eu/smart-buildings-making-buildings-smarter-greener-and-more-energy-efficient/

Current state of IoT devices

Total number of device connections (incl. Non-IoT)

20.0Bn in 2019– expected to grow 13% to 41.2Bn in 2025

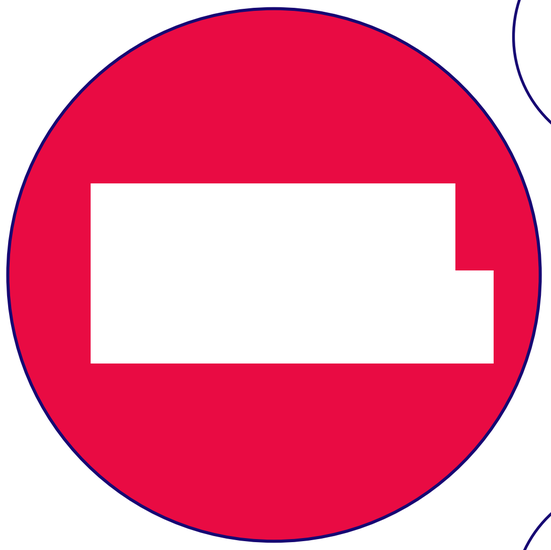


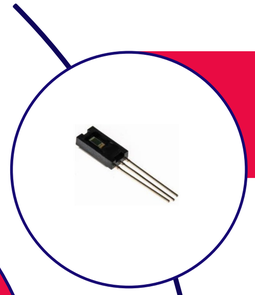
Note: Non-IoT includes all mobile phones, tablets, PCs, laptops, and fixed line phones. IoT includes all consumer and B2B devices connected – see IoT break-down for further details

Source(s): IoT Analytics - Cellular IoT & LPWA Connectivity Market Tracker 2010-25

https://iot-analytics.com/state-of-the-iot-2020-12-billion-iot-connections-surpassing-non-iot-for-the-first-time/

IoT challenges



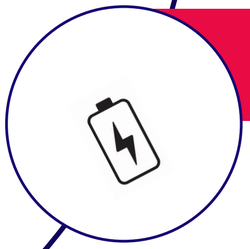


Sensors

price, size, power consumption

Transceivers

price, size, power consumption



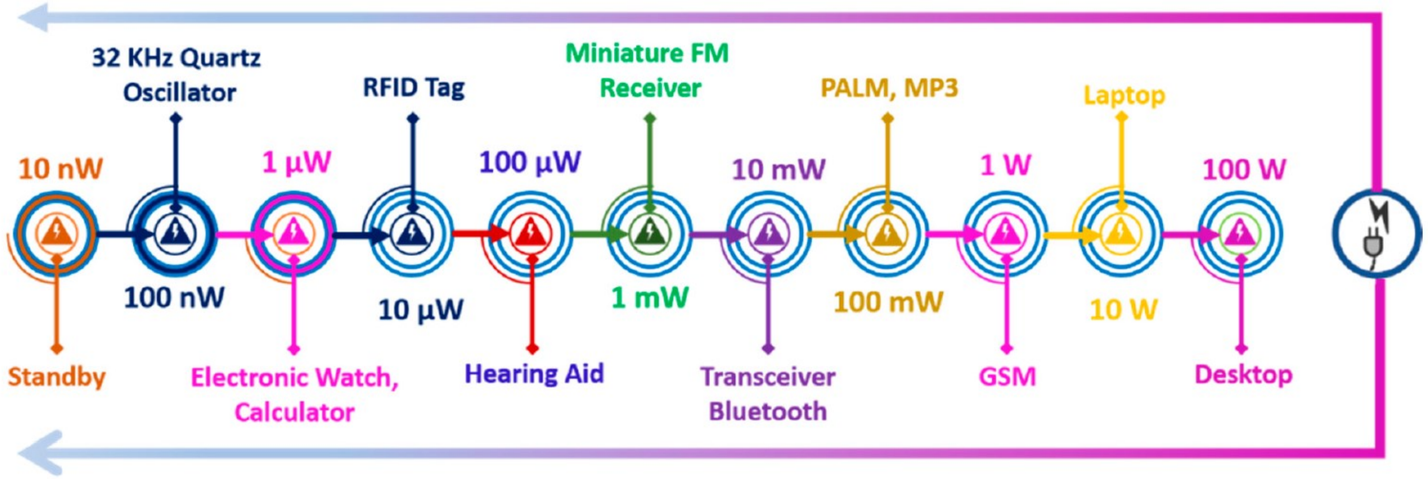
Power autonomy

power consumption + remote areas
Batteries have a limited lifespan…alternative?

- How much is the power needed?
- Which energy sources can we use?

Power Requirements of IoT devices

Typical IoT devices or low-powered electronic devices require power ranging between 10 nW and 100 W:



MK Mishu et al (2020)

Energy Sources: Energy Harvesting

Much research has been done on collecting energy from the environment in order to provide unlimited lifetime for these devices: this is known as ***energy harvesting***.

There are many forms of energy that can be harvested:

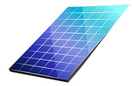
Energy Source	Scavenging Device
Light	Solar Cell
Vibration or Motion	Piezoelectric Electrostatic
	Piezoelectric Electromagnetic
Thermal	Thermoelectric
Radio Frequency	Antenna

There is not a single energy source satisfying the needs for all IoT devices

MK Mishu et al (2020)

Popular Energy Harvesting Sources

Energy Source	Scavenging Device
Light	Solar Cell



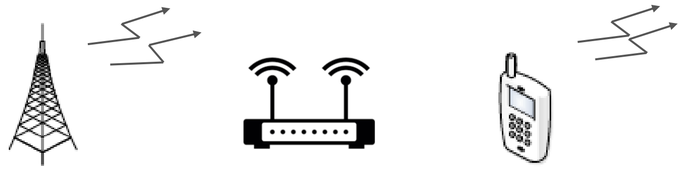
Energy Source	Scavenging Device
Thermal	Thermoelectric

Energy Source	Scavenging Device
Radio Frequency	Antenna

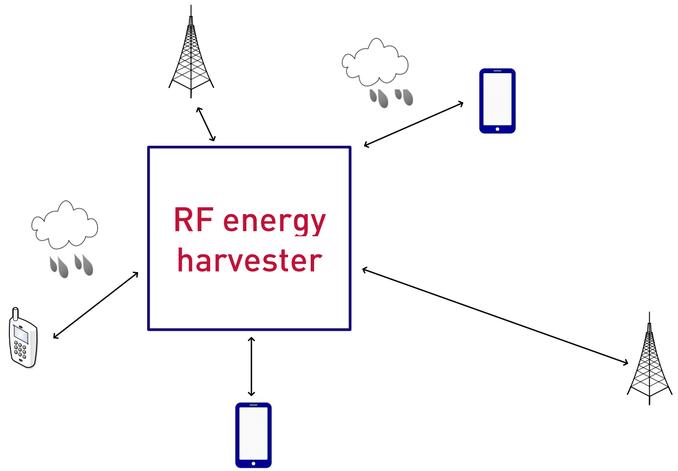
Radio Frequency (RF) Energy Harvesting

Energy Source	Scavenging Device
Radio Frequency	Antenna

RF energy harvesting refers to the usage of available RF energy from *existing* RF sources:



Scenario where many RF sources are present in the environment:



Radio Frequency (RF) Energy Harvesting

Energy Source	Scavenging Device
 Radio Frequency	Antenna

Advantages

- Free ‘energy’ source

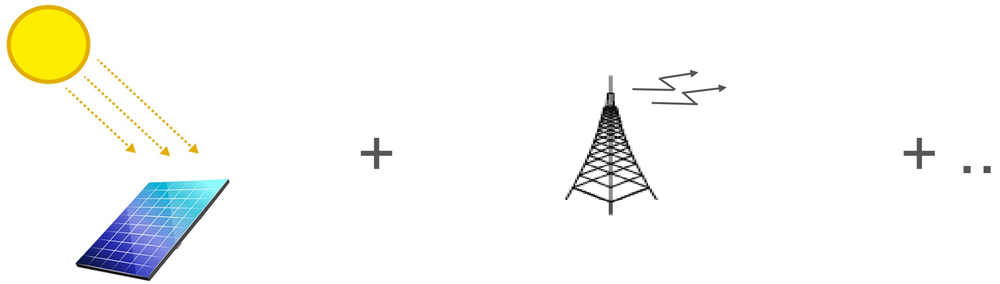
Challenges

- Low power density
- Variable/unpredictable power

Hybrid Energy Harvesting

To overcome the power limitations, energy can be collected from more than one sources: this is known as *hybrid* energy harvesting.

Example: Solar/RF hybrid system

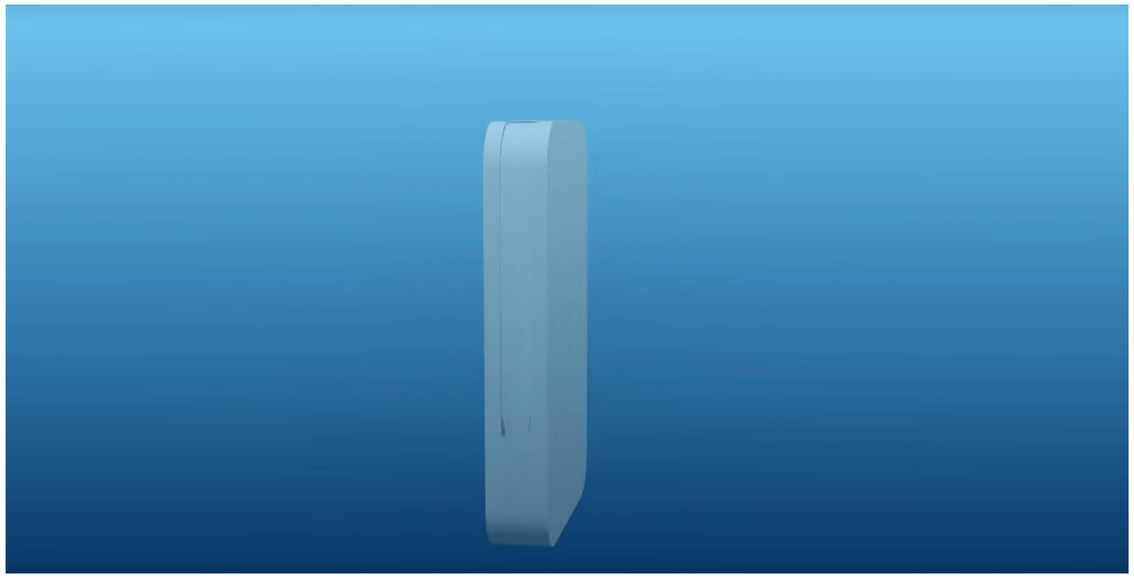


Challenge: efficient power combination

Wireless Power Transfer (WPT)

- Wireless Power Transfer (WPT): intentionally transmitting energy to provide the required power.

- In *far-field WPT* (opposed to ambient energy harvesting), the power is provided by the operator of the harvester.



N. Shinohara (2020)
National Geographic, www.youtube.com/watch?v=xi6r3hZe5Tg

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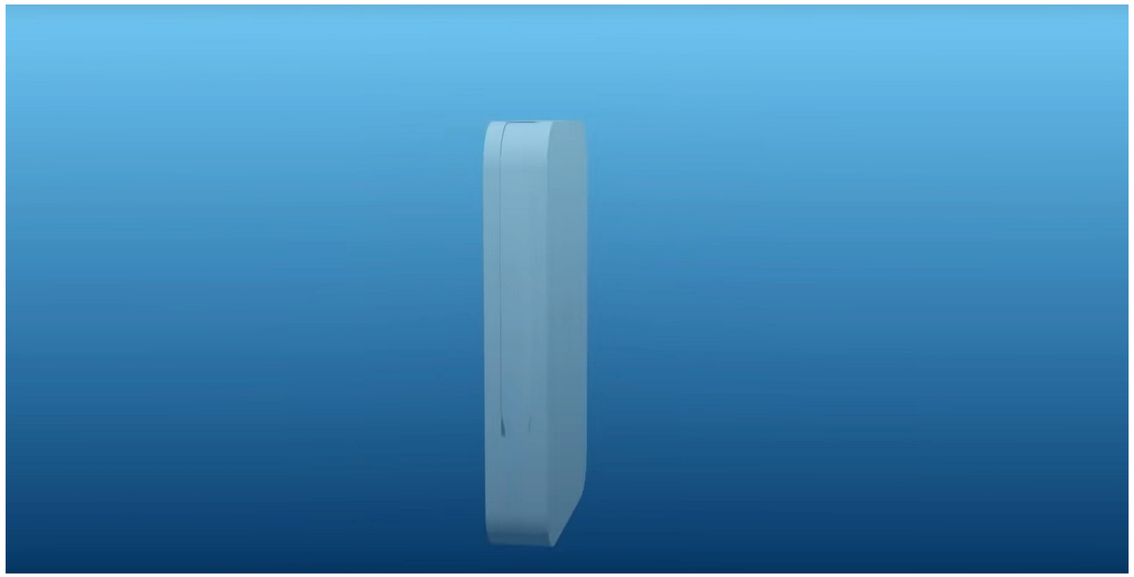
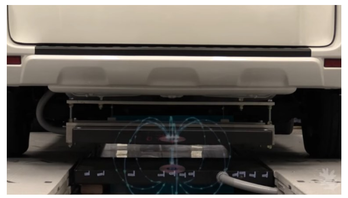


Important note: *Far-field WPT* is not the same with the near-field WPT (use of coils).

Example of near-field WPT:

Source: Witricity company



Source: Oak Ridge National Laboratory (ORN)

N. Shinohara (2020)
National Geographic, www.youtube.com/watch?v=xi6r3hZe5Tg

Wireless Power Transfer (WPT)

RF Energy harvesting versus far-field WPT

They both collect RF energy:

- RF EH: the energy comes from *existing sources.*
- WPT: energy comes from dedicated energy sources that *transmit this energy on purpose.*

In RF Energy Harvesting, the energy is ‘free’ but varies over time, location etc

WPT offers reliability (we can control the transmitter side) at the expense of energy and cost..

https://www.eetimes.eu/how-far-can-we-take-wireless-power-transfer-technology/

The rest of the talk - overview

- Radio Frequency Energy Harvesting system
- Far-Field Wireless Power Transfer system
- Conclusions

RF Energy Harvesting

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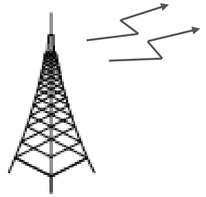
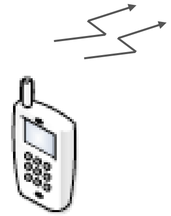
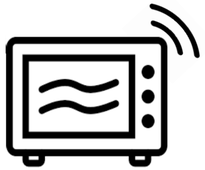


Base stations



Cellular phones

Routers



Microwave Ovens

RF Energy Harvesting

Existing RF sources

Transmitter(s)

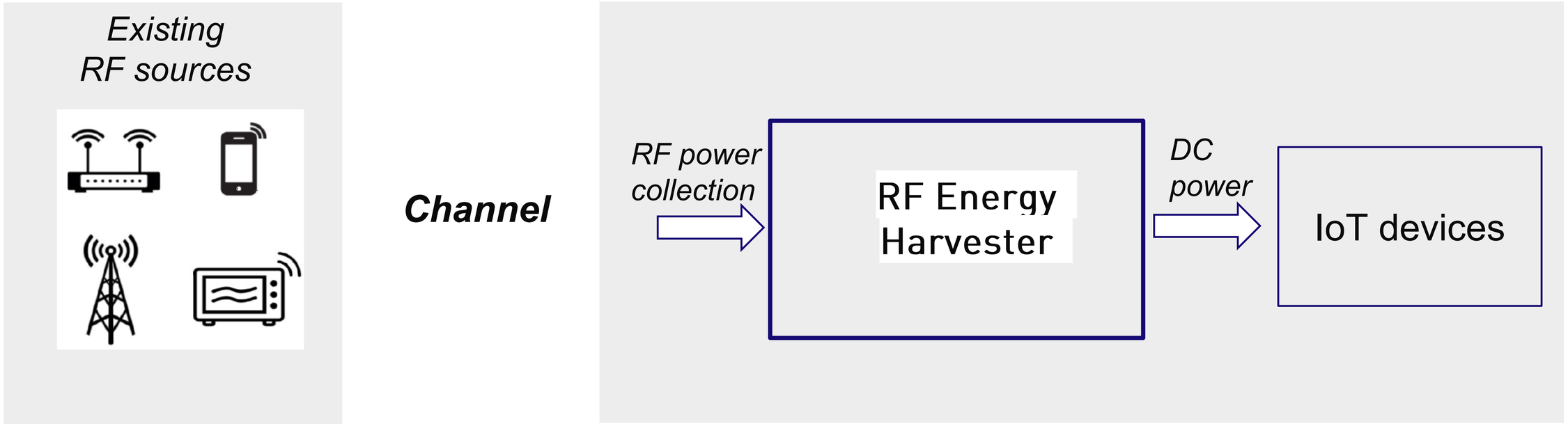
RF Energy Harvesting

Existing RF sources

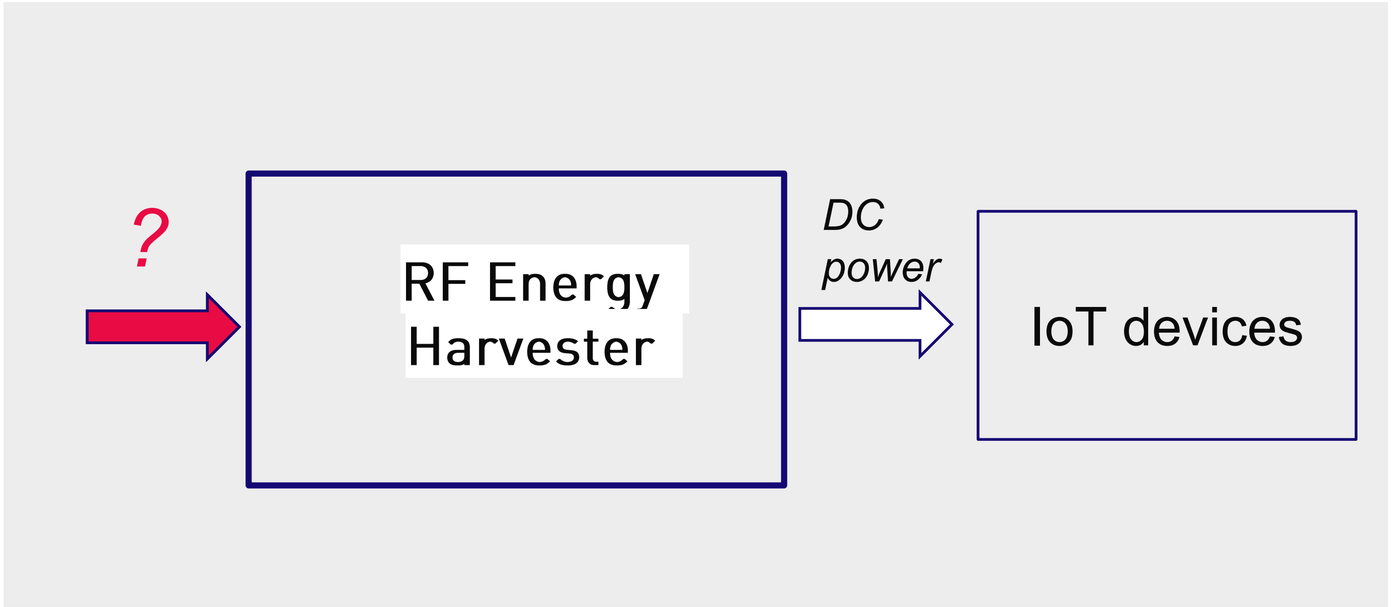
Channel

Transmitter(s)

RF Energy Harvesting



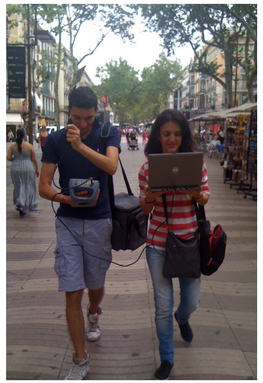
RF Energy Harvesting

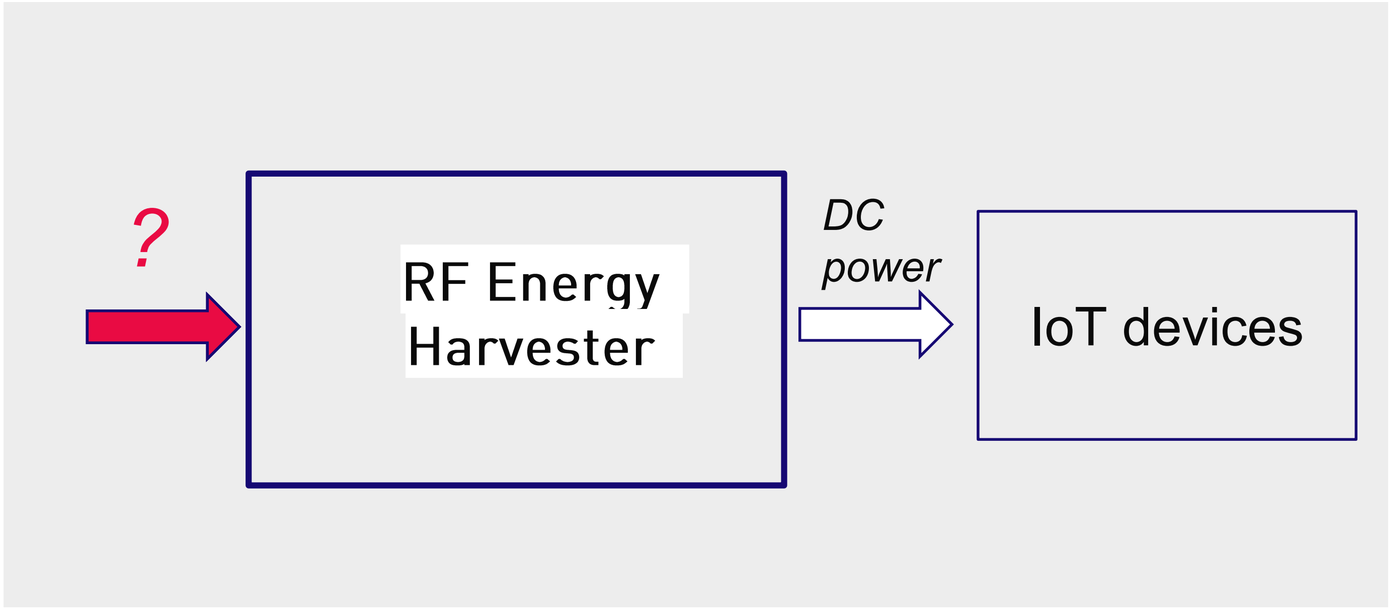


Receiver

J. Finnegan (2021)

RF Energy Harvesting





Receiver

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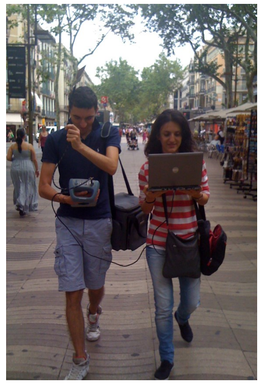
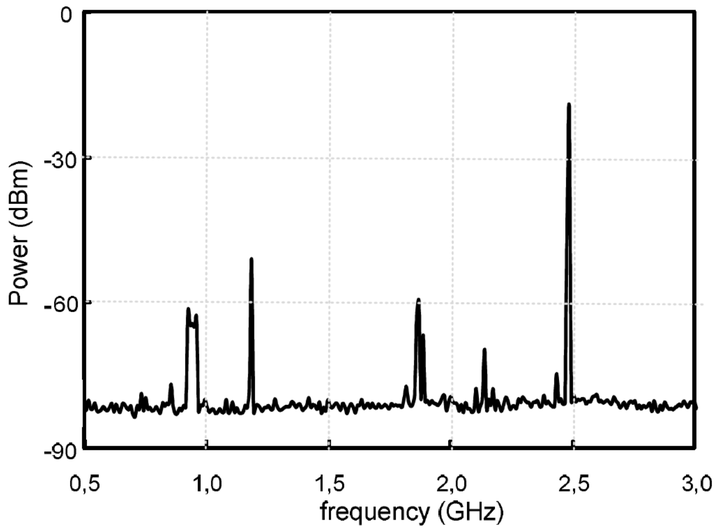
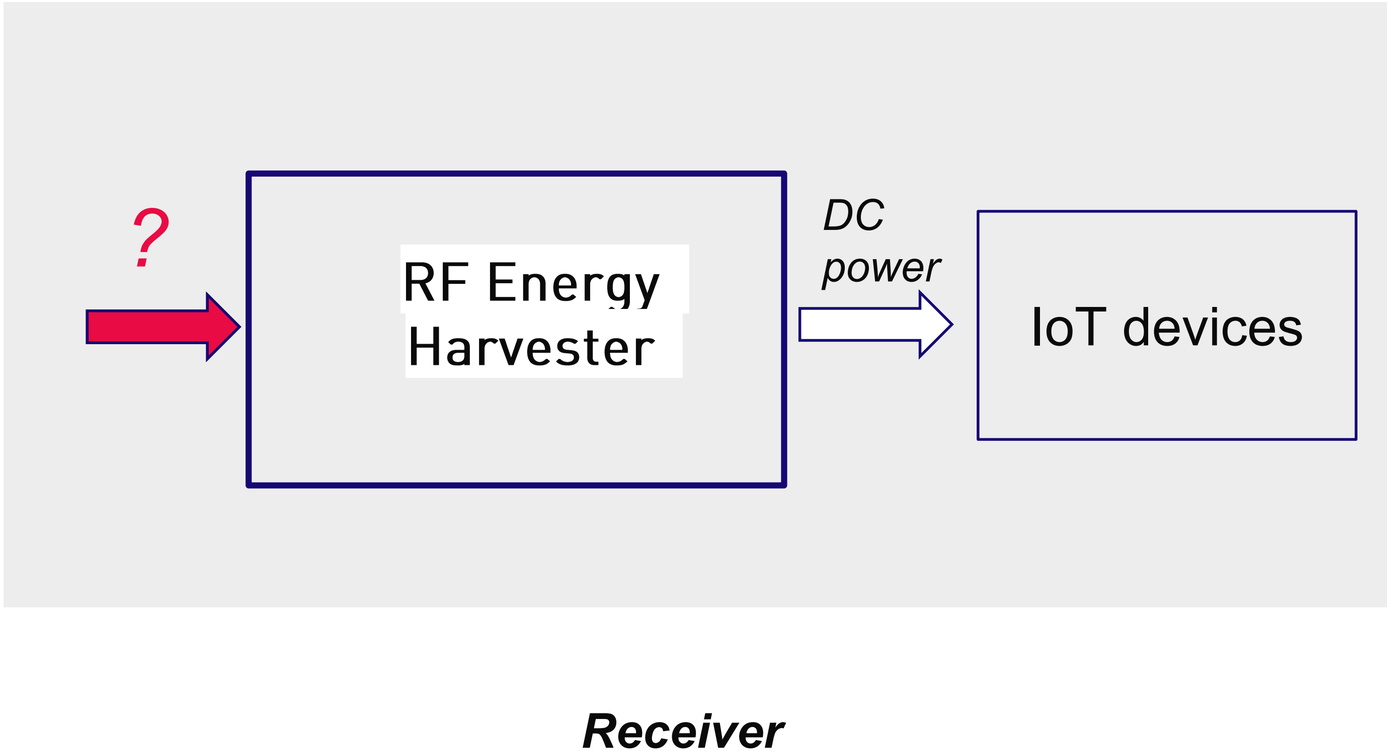
RF Energy Harvesting



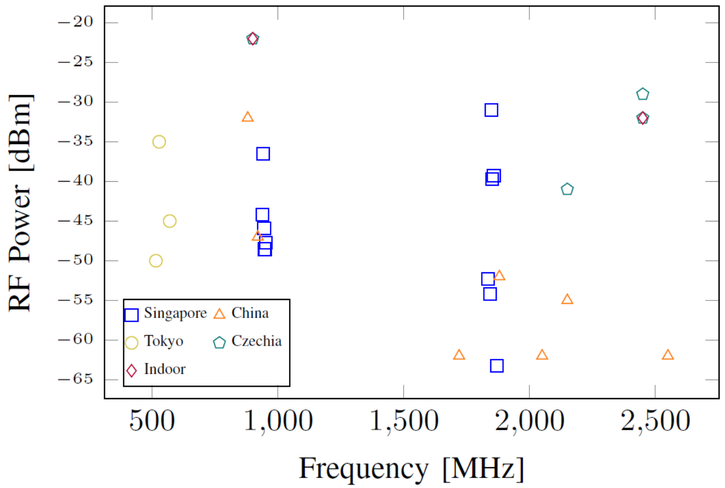


L. Guenda (2012)

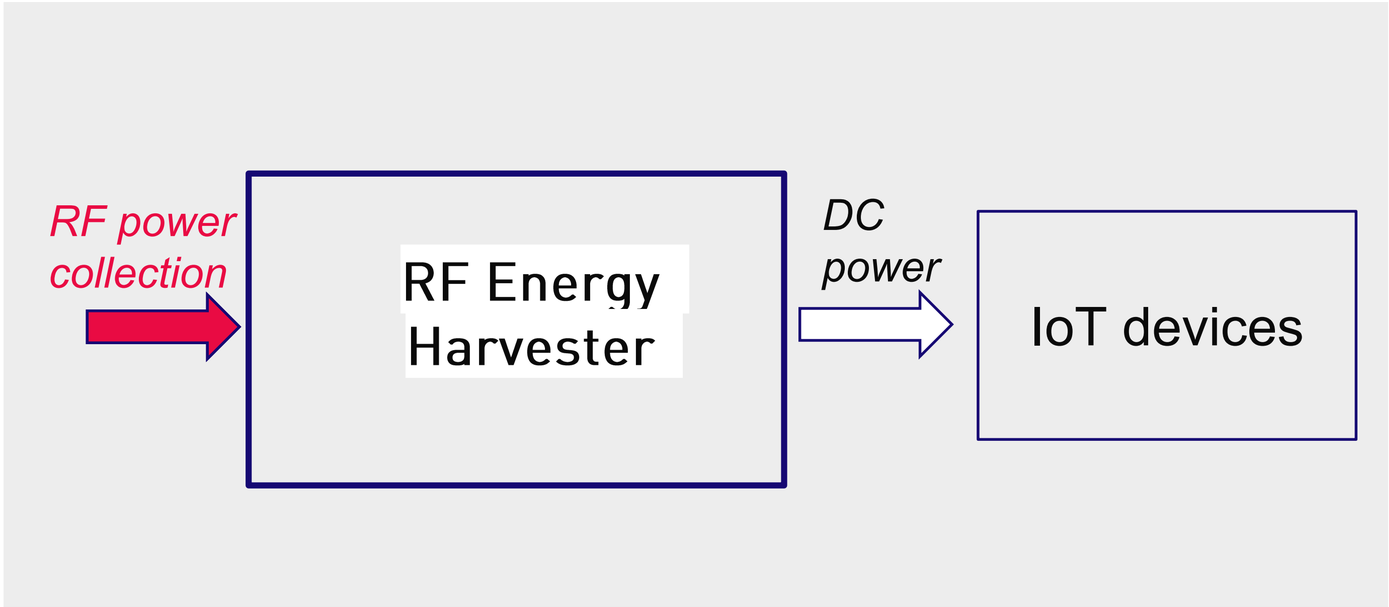


Receiver

RF Energy Harvesting



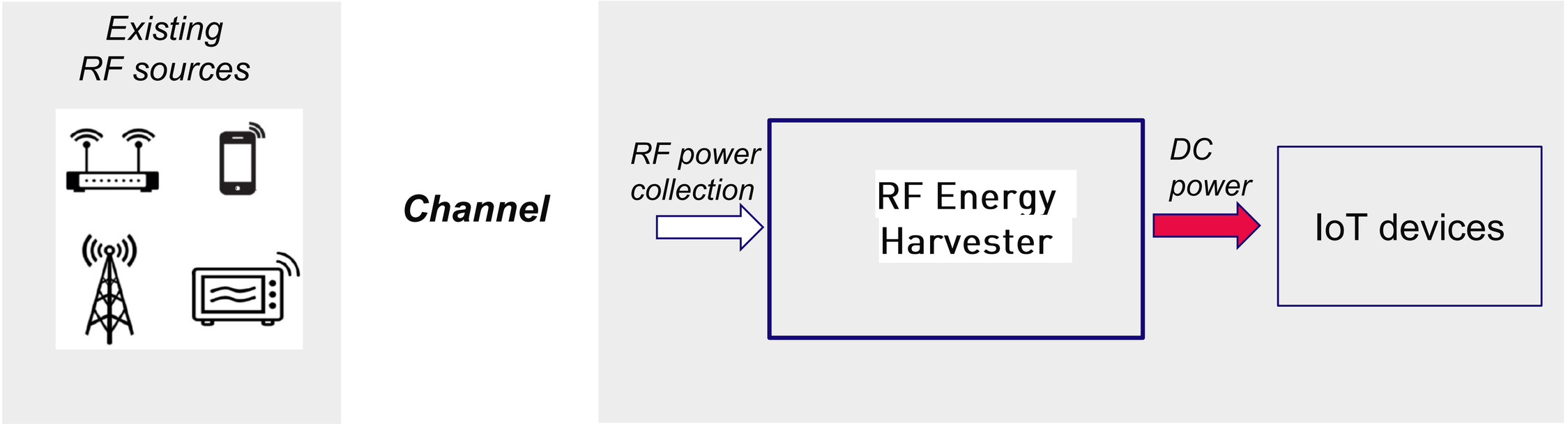
- Worldwide measurement campaigns
- Power variability over location, time, frequency etc



Receiver

J. Finnegan (2021)

RF Energy Harvesting



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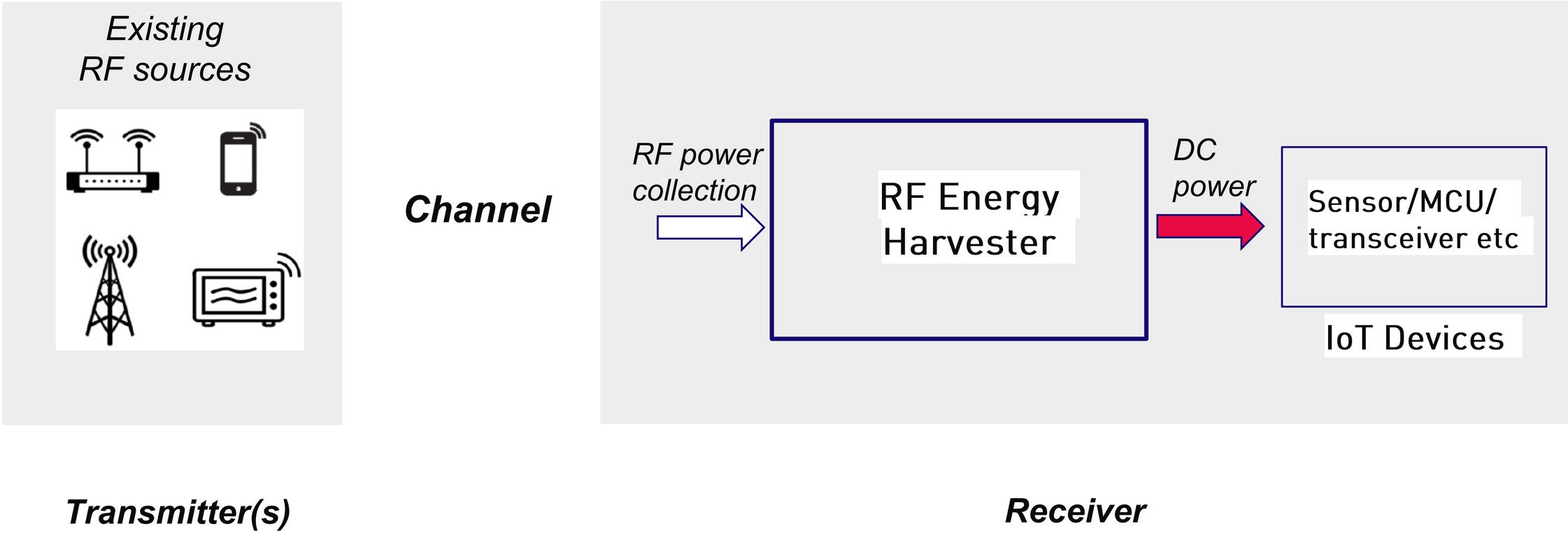
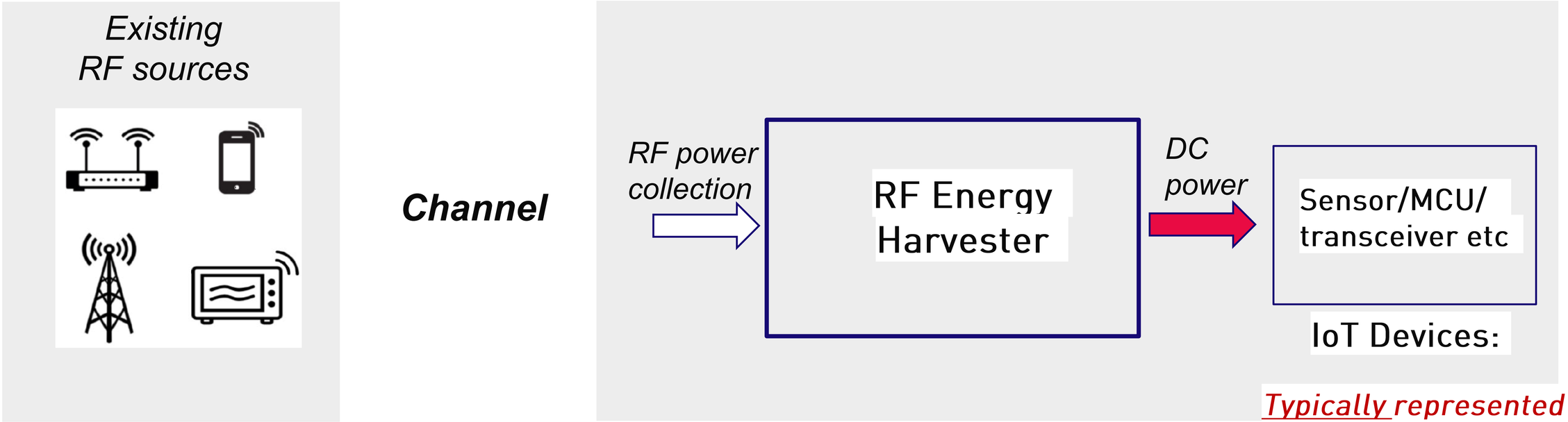
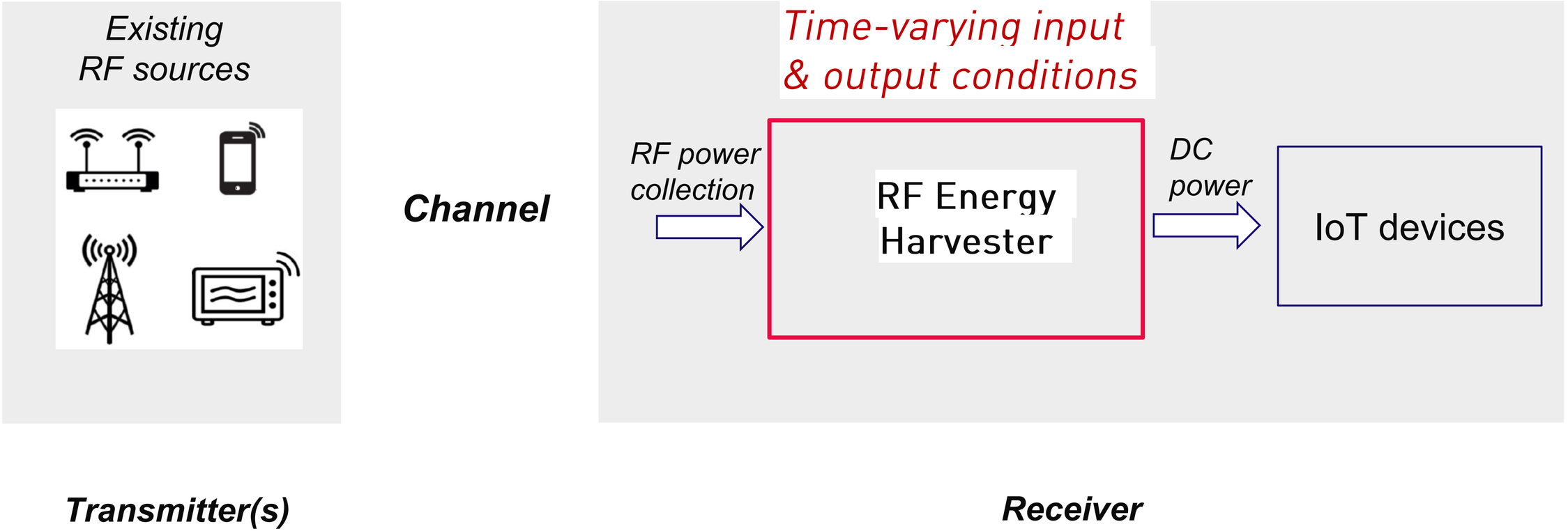


RF Energy Harvesting



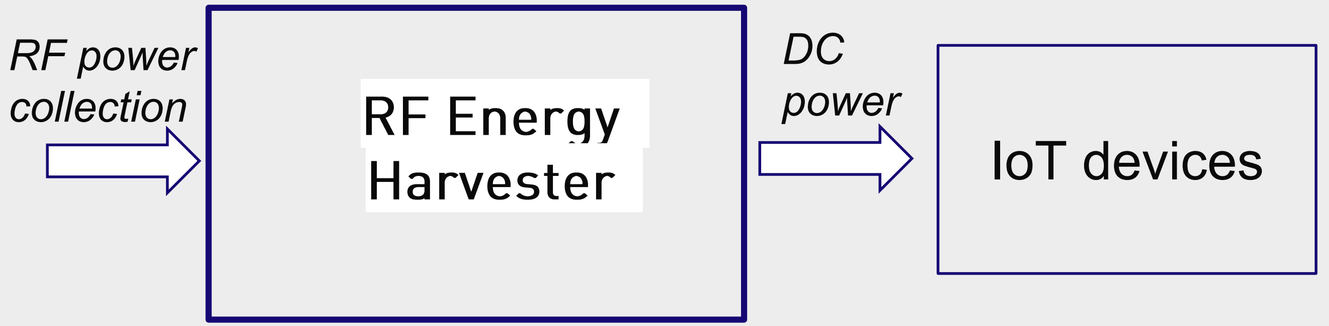
RF Energy Harvesting



RF Energy Harvesting system

Existing
RF sources

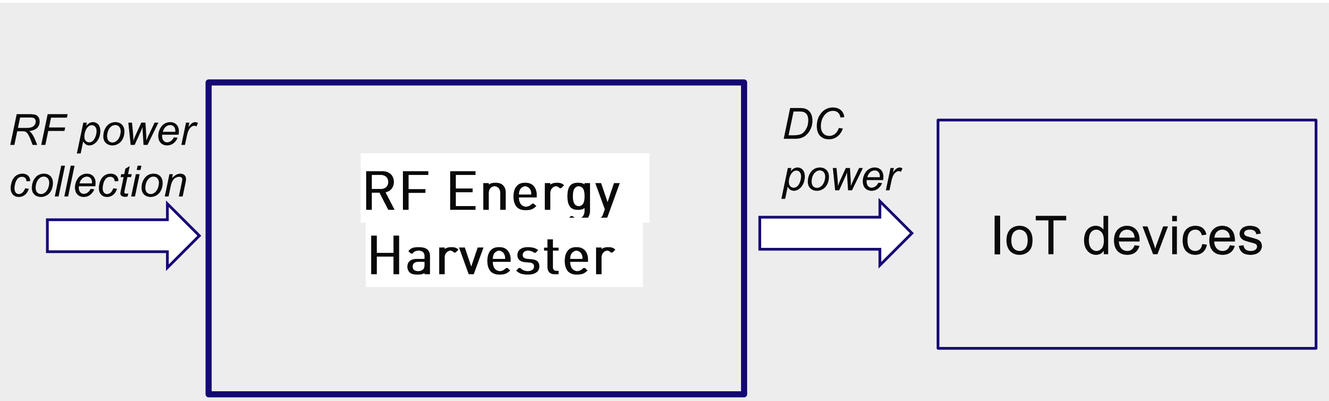
Channel



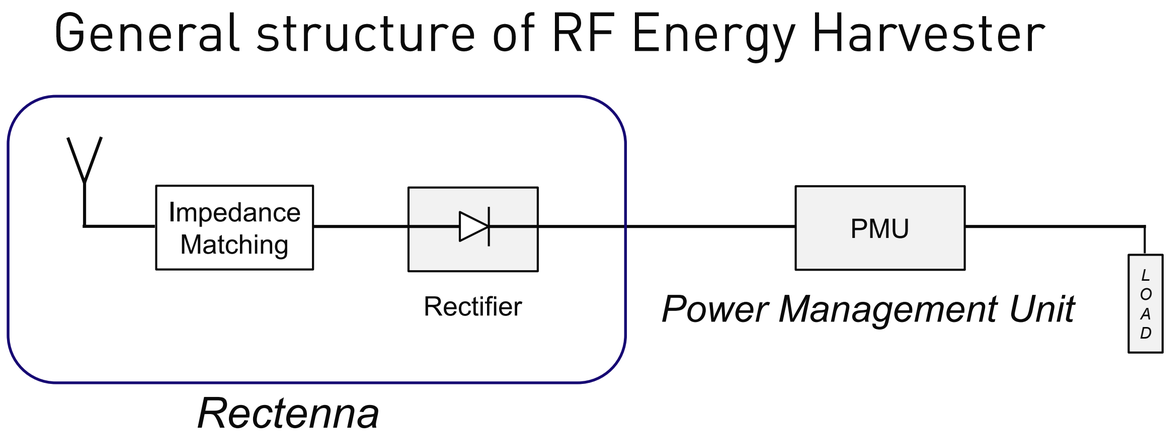
Wireless Power Transfer system

Dedicated
RF source

Channel



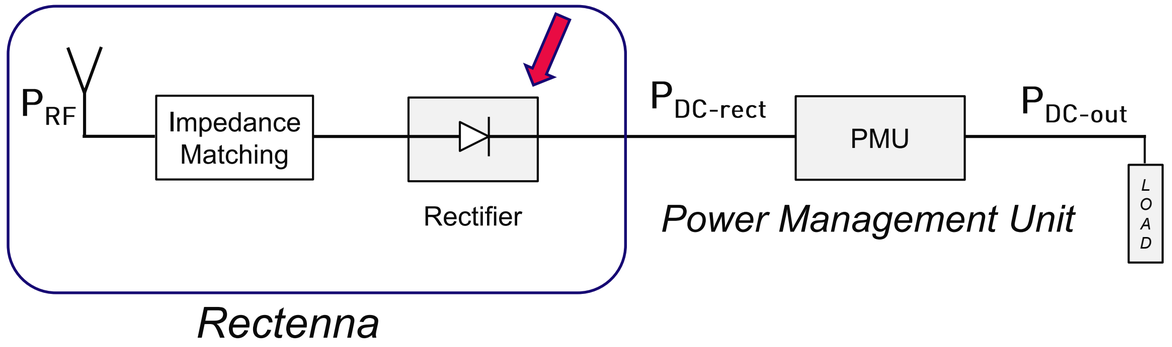
RF Energy Harvester



- The ***rectenna*** (antenna + impedance matching + rectifier) collects RF signals and transform them to dc power using a certain rectifying element, such as Schottky diodes.
- The output of the rectenna can be connected to a ***power management unit***, ***dc-dc converter*** etc. The harvested dc power can be stored in an energy storage element (i.e. capacitor).
- The **load** represents the connected sensor.

RF Energy Harvester

General structure of RF Energy Harvester



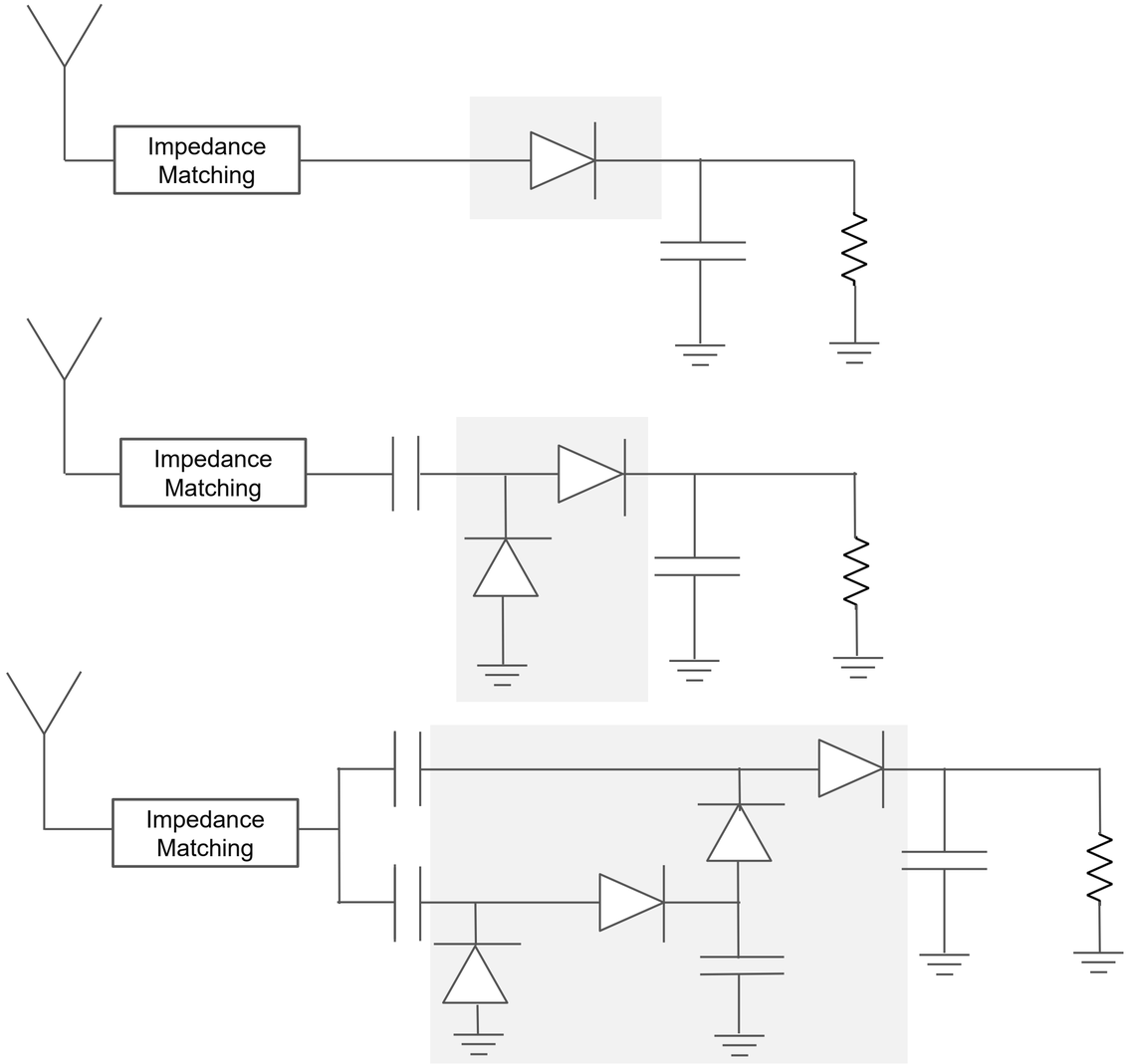
Rectenna Efficiency:

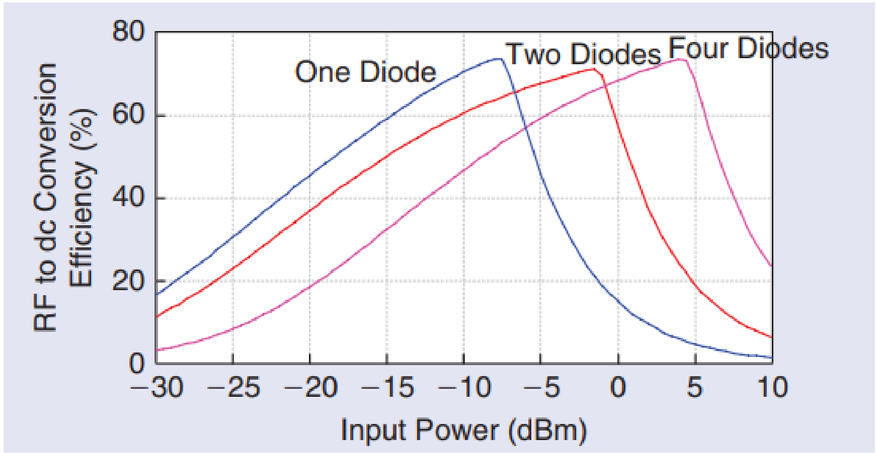
$$\eta_{rectenna} = \frac{P_{DC-rect}}{P_{RF}}$$

PMU Efficiency:

$$\eta_{PMU} = \frac{P_{DC-out}}{P_{DC-rect}}$$

Rectenna Challenges: *Optimum Topology*



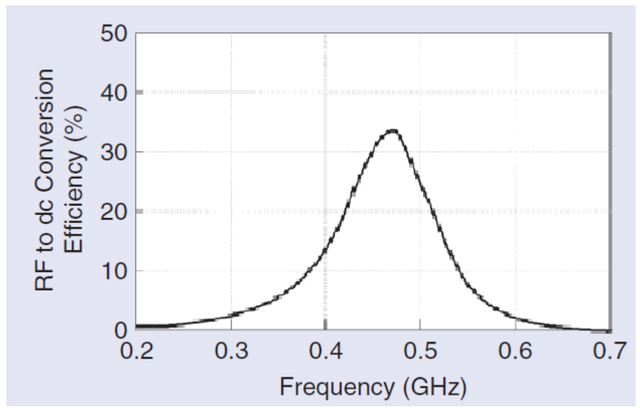


The selection of the topology is important, while the optimum topology depends on various parameters: such as input power and output load.

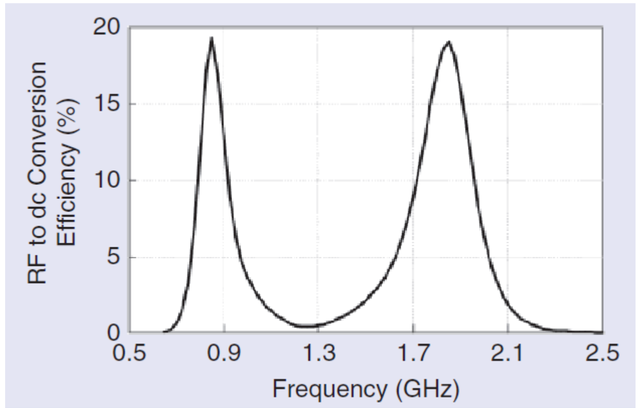
A. Boaventura (2013), K. Niotaki (2021)

Rectenna Challenges: *Bandwidth of Operation*

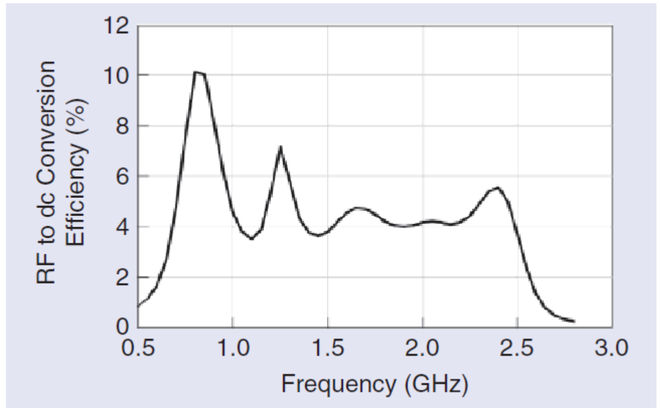
Energy harvesters capable of harvesting simultaneously from different frequency bands.



Single-Frequency



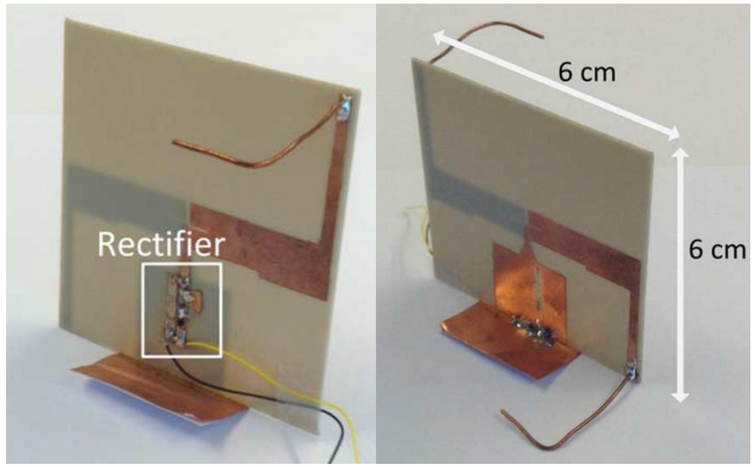
Dual-Band



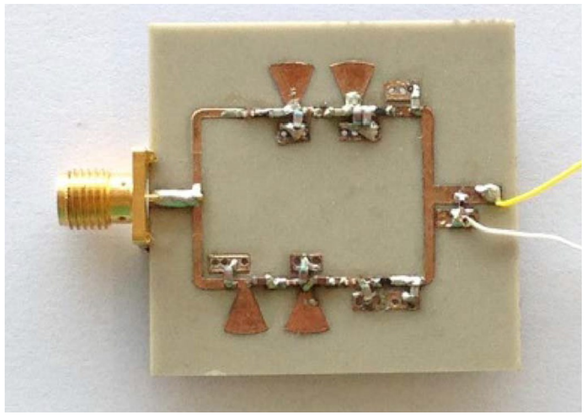
Broadband

A. Boaventura (2013)

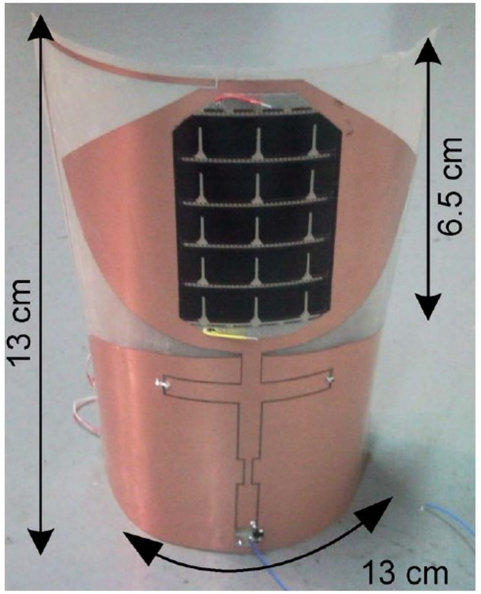
RF Energy Harvesting circuits



Dual-Band Rectenna



Dual-Band Rectifier

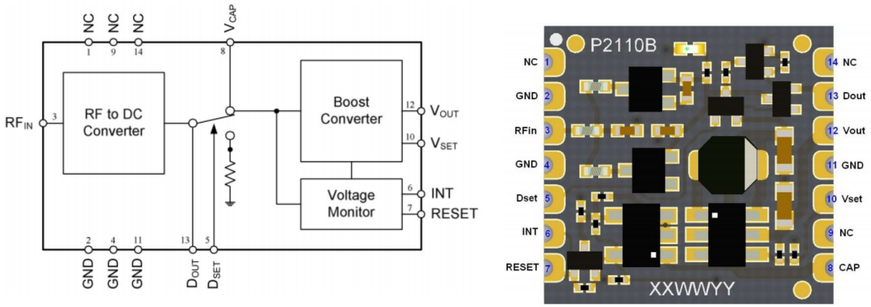


Dual-band solar/EM energy harvester

A. Collado (2013), K. Niotaki (2014)

RF energy harvesting: commercial products

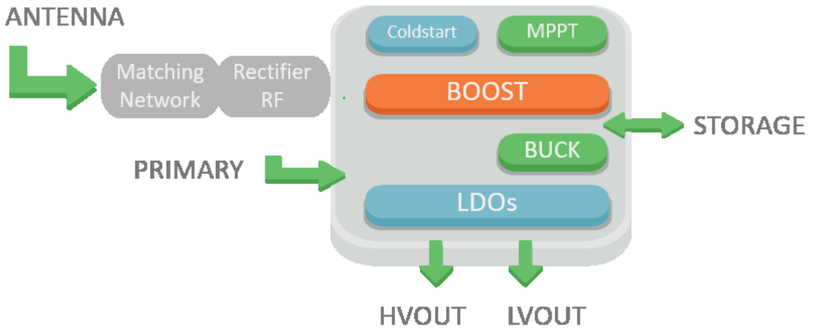
RF energy harvester



P2110B from PowerCast Corp.

Specs: 900 MHz, -12 dBm of input power,
output voltage 2-5.5 V and up to 50 mA

RF energy harvester

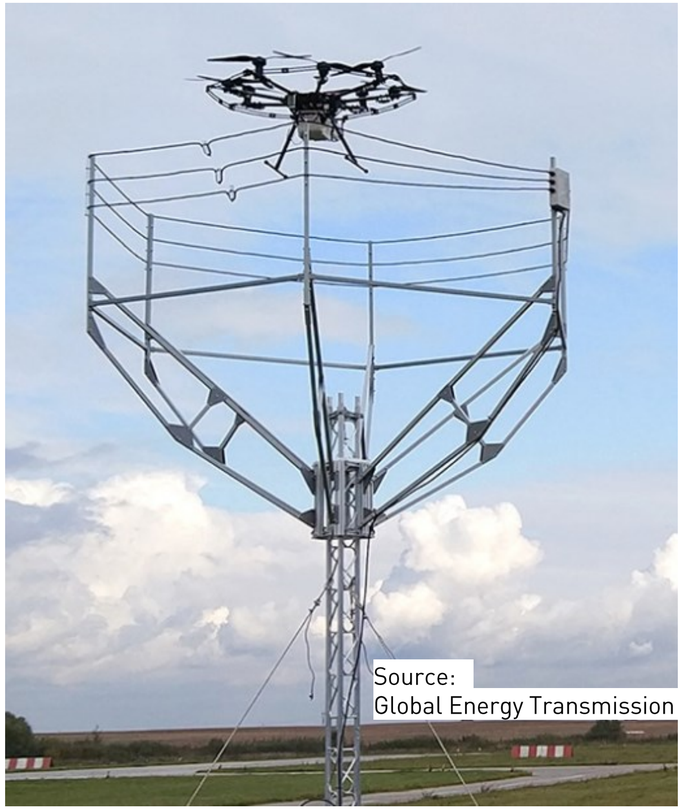


AEM30940 from e-peas

Specs: 800 MHz, 900 MHz & 2400 MHz,
input power range: -19 dBm to 10 dBm
output power: 20 mA @ 1.2/1.8 V, 80 mA @ 1.8-4.1 V

https://e-peas.com/types/energy-harvesting/rf/
https://www.powercastco.com/wp-content/uploads/2016/10/P2110B-Datasheet-Rev-3.pdf

Wireless Power Transfer



Source:
Global Energy Transmission

Source: https://energous.com/

Source: www.powercastco.com

Companies: Global Energy Transmission, Energous, Powercast, OSSIA, e-peas etc

http://getcorp.om/

Wireless Power Transfer at millimeter wave frequencies

5G systems leveraged the potential of the millimeter waves for *WPT* and *RF EH:*

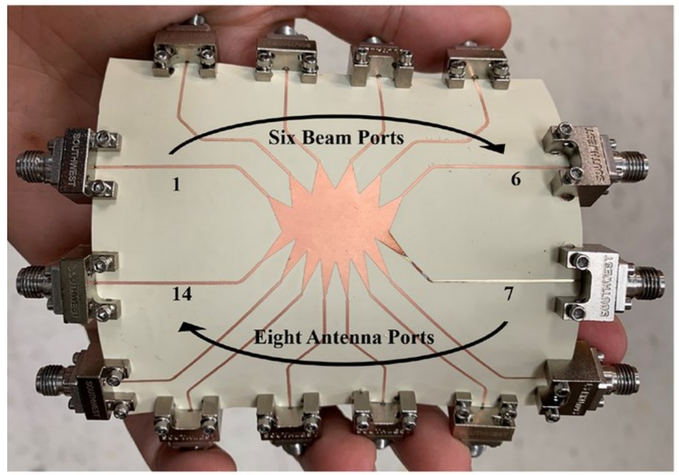
- large swaths of spectrum available
- large antennas arrays in small form factors
- sensitive to blockages

Research challenges

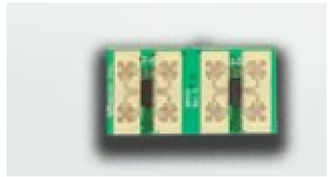
- low-cost rectennas
- high end-to-end efficiency
- impact on existing communication systems
- safety and health guarantees

Y. Zeng (2017), M. Wagih (2020), A. Eid (2021)

Wireless Power Transfer at millimeter wave frequencies



28 GHz rectenna
A. Eid (2021)



24 GHz Wireless power solution
Source: Guru Inc.

https://www.eetimes.com/millimeter-wave-spectrum-for-wireless-power-solution/#
https://guru.inc/#technology

Conclusions

- Power autonomy of low-power devices
- Potential solutions:
  - Energy harvesting
  - Wireless Power Transfer
- Further research needed

Thank you!

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