ARCES: Circuits, systems and sensors for the emerging energy and information challenges

ARCES Day, Feb 17th 2023

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Dipartimento di Ingegneria dell'Energia Elettrica e dell'Informazione "G. Marconi"

Outline

1. Introduction
2. Key competences in ARCES
3. Technologies and achievements

Circuits, systems, and sensors

Key components of the digital transition

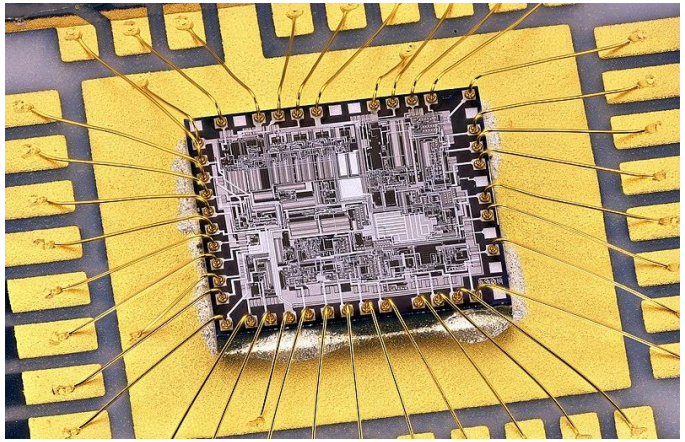
Building blocks of every 'smart' system

Among the core competences of ARCES since its foundation

Multi-disciplinary research teams pursuing innovation and tackling challenges of energy efficiency and in information engineering, with **internationally recognized results**

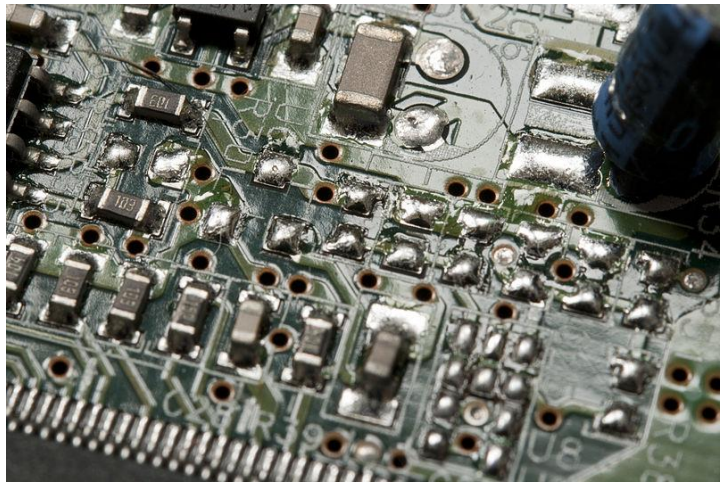
Integrated circuits, system-level design, wireless concepts, sensors and algorithms

ASICs



Mister rf, CC BY-SA 4.0, via Wikimedia Commons

circuits & systems



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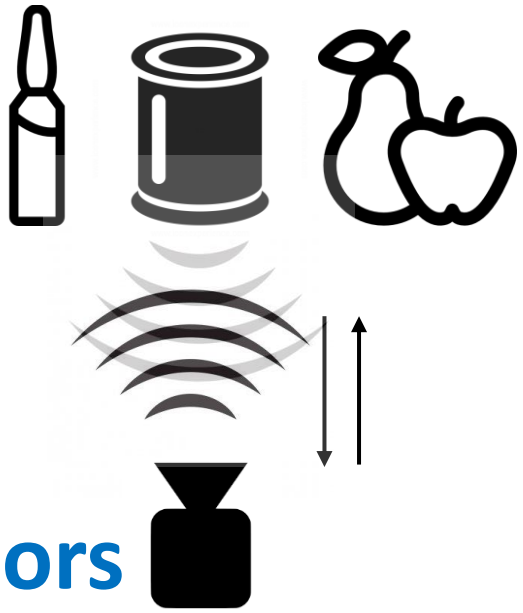
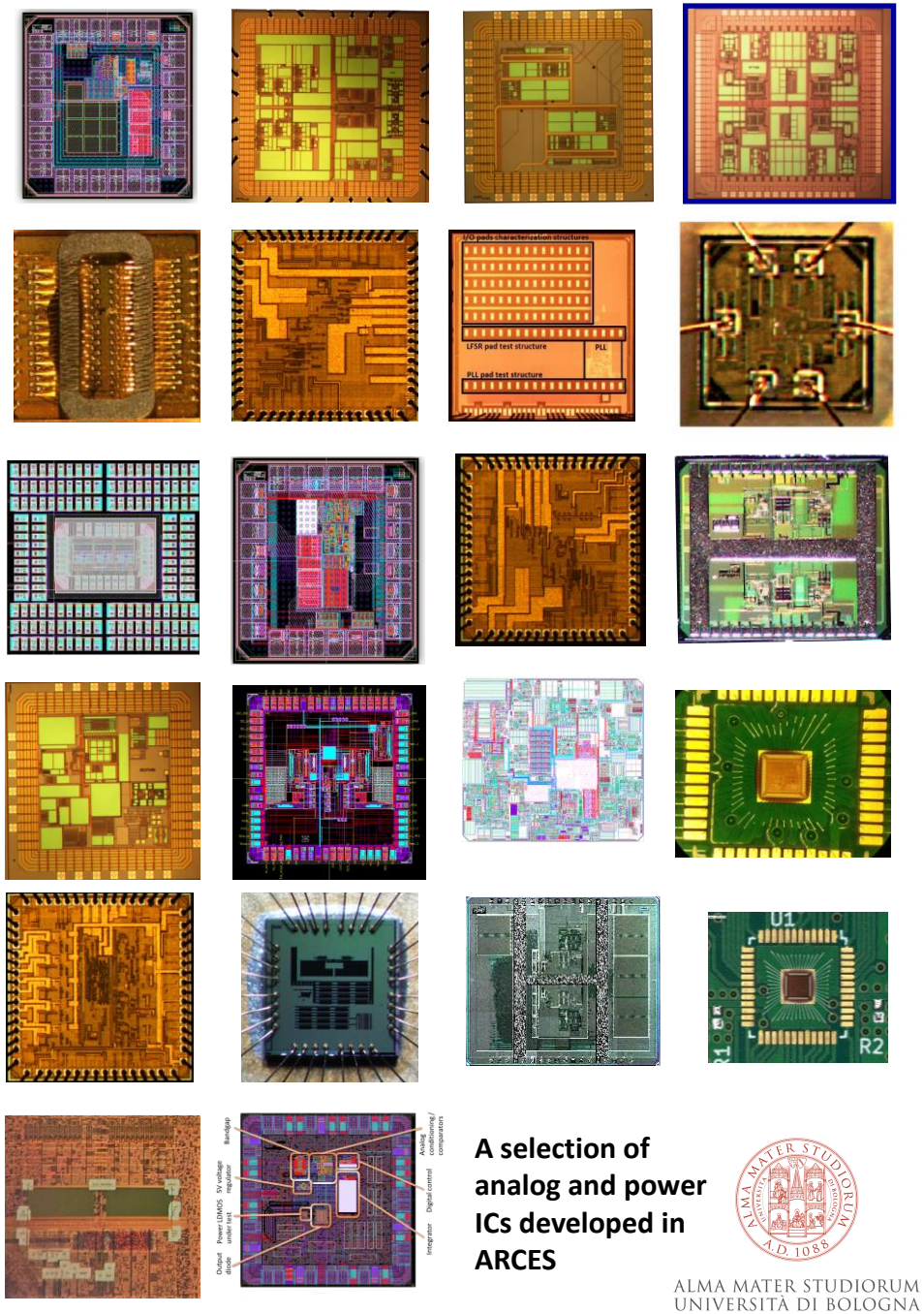
sensors



Integrated Circuit Design

- Design of innovative custom integrated circuits represents a relevant share of ARCES activities
- The capability of facing design at transistor level at sub-µm scale allows the maximum degree of flexibility and performance for the target applications
- This area has relevant input barriers, including know-how, CAD tools and critical mass: ARCES among the few players in Italy with a succesful record of academic results and industrial collaborations
- Important collaborations with industry
- Strategic area in light of the EU Chips Act and national follow-up intiatives to increase leadership and autonomy for Europe in chip development & production
- Competences in analog design highly required by industry
- Experience across a wide range of microelectronic technologies for applications ranging from analog circuits for sensors, smart-power circuits, digital computation



A selection of analog and power ICs developed in ARCES

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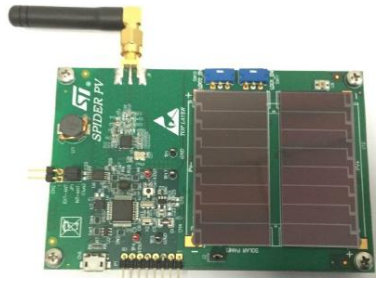
System-level design

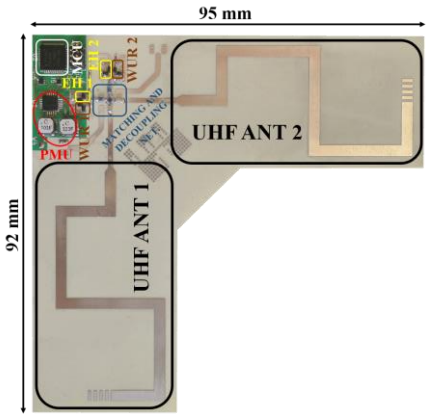
Design of electronic systems and novel applications is another of the main core competences of ARCES

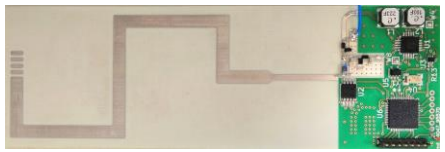
A wide range of systems was and is continuously being developed at our premises

This includes:

- Micropower converters
- Energy-efficiency Internet-of-Things
- Environmental and energy monitoring
- Sensing applications
- Wireless solutions







Samples of electronic systems developed in ARCES

ICT for Energy Efficiency

Energy efficiency and efficient use of resources among the main drivers of ARCES research.

Share of ICT energy consumptions worldwide is progressively increasing and projected towards >10%*

* *L. Belkhir, A. Elmeligi, Assessing ICT global emissions footprint: Trends to 2040 & recommendations, Journal of Cleaner Production, vol. 177, 2018*

In the H2020 ENABLES project we estimated **1 Trillion IoT devices** in the world by **2025**, with average battery life of 2 yrs

ENABLES Position paper

This results in **>78M** batteries to be manufactured and disposed of every day by 2025 → environmental issues, need for materials

It is then essential that our portable devices, sensors, and systems are designed to consume less energy or to extract energy from their surrounding enviroments when possible.

ARCES fully committed towards this objective by means of competitive research and industrial collaborations

M. Hayes, Tyndall Institute, coordinator of H2020 ENABLES

EnABLES
European Infrastructure Powering the Internet of Things (H2020, ga 730957)

Funded by the European Union

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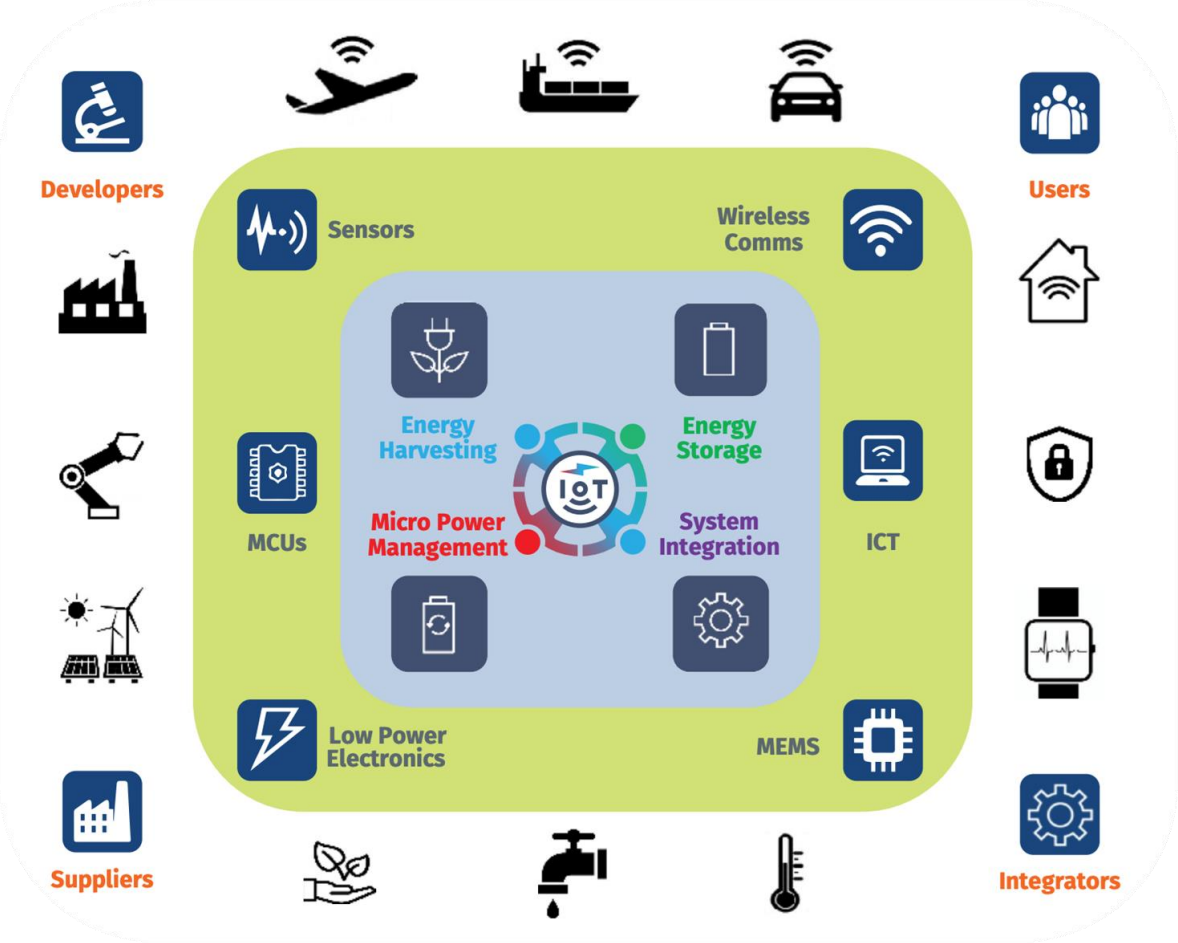
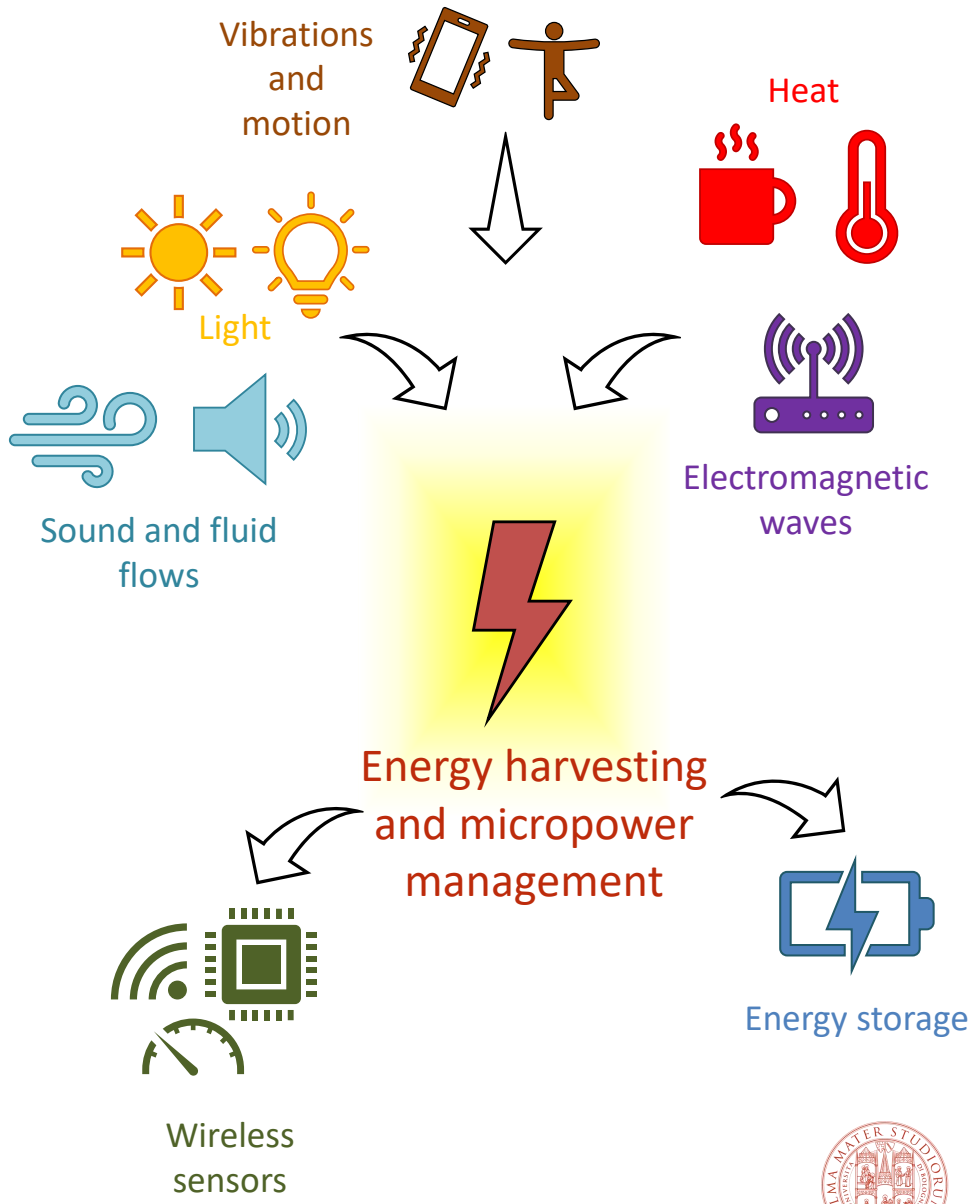
Energy harvesting

Energy harvesting is the capability of an electronic system to extract power from the surrounding environment.



H2020 ENABLES, White paper



Energy harvesting

Key competences in ARCES

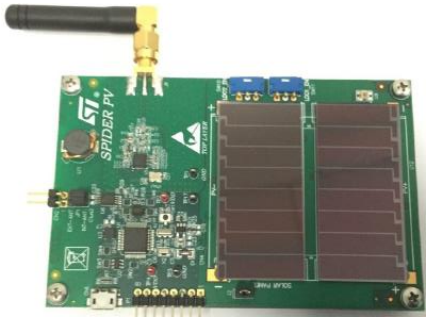
ASIC design for utra-low power and ultra-low voltage sources

- **Achieved operation with 1 µW input power and start-up down to 8 mV sources**
- **Scalable multi-source integration up to 9 sources**

Optimized micropower management based on COTS

- Vibration, RF, thermal PV
- Full integration with IoT nodes

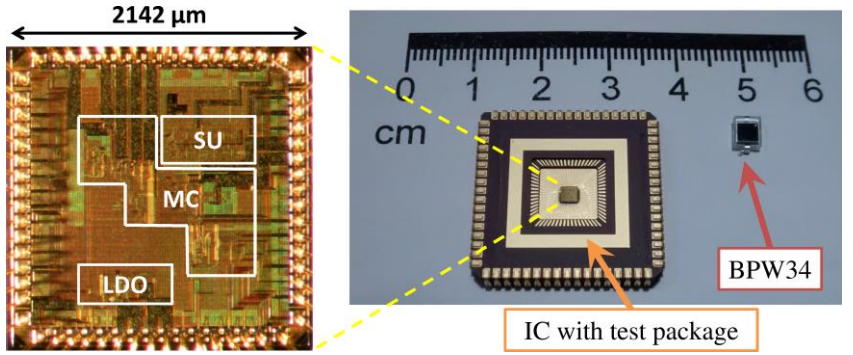
Optimized wireless sensing nodes

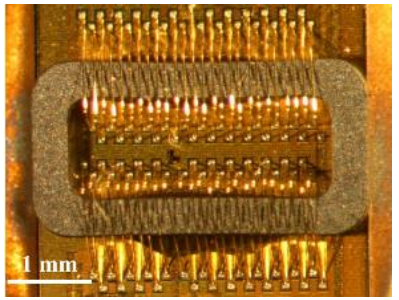


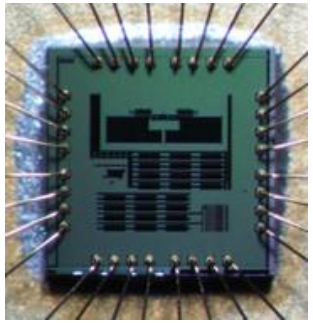
PV module

TEG module

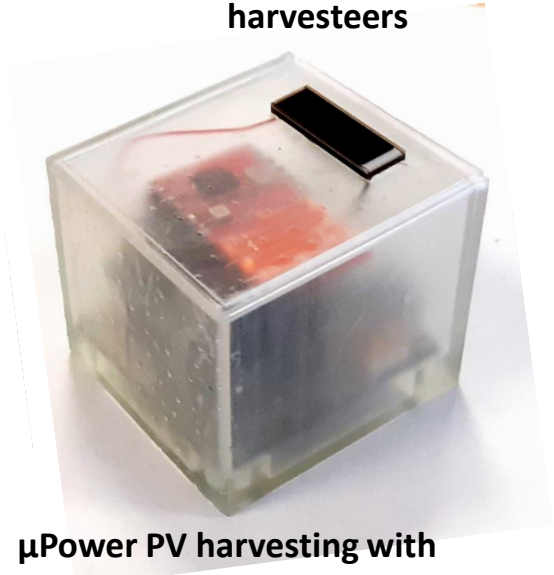
Vibrational harvesteers







Nanopower and ultra-low voltage EH ASICs



µPower PV harvesting with environmental sensing and sub-GHz wireless

Multi-source EH module

European Infrastructure Powering the Internet of Things (H2020, ga 730957)

ECSEL CONNECT (ga 737434)

ECSEL ENERGY ECS, ga 101007247)

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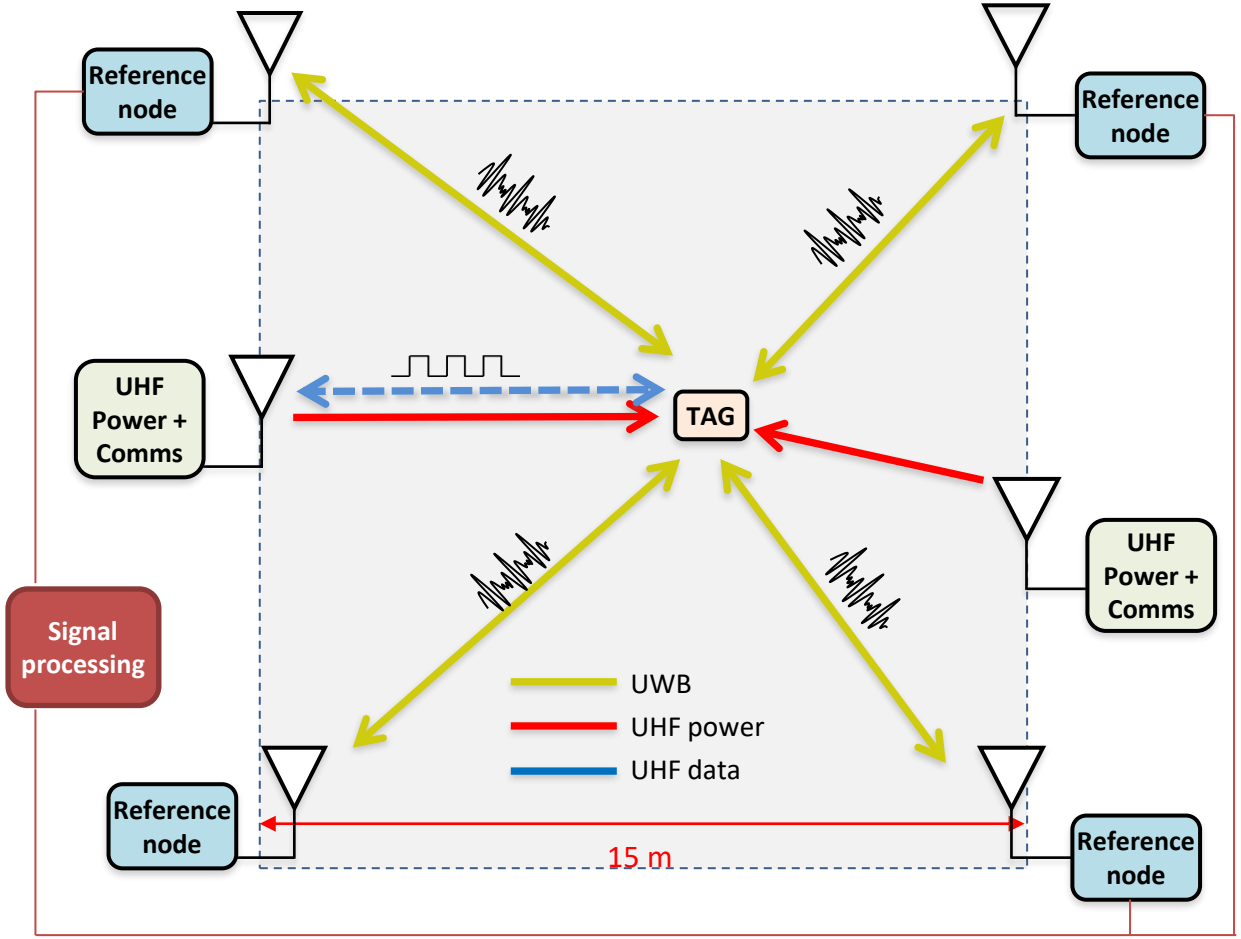
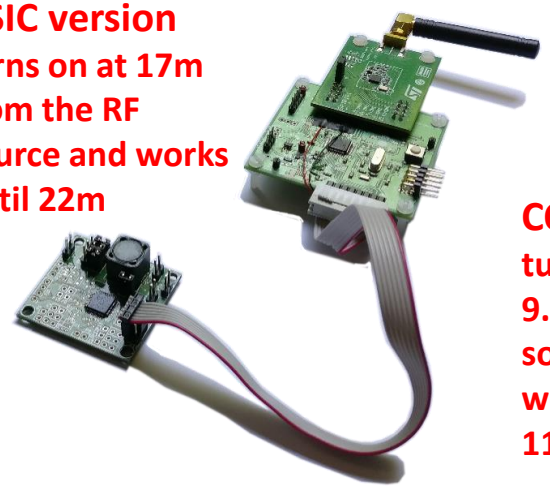
Energy harvesting: RF-powered sensor tags with localization capabilities

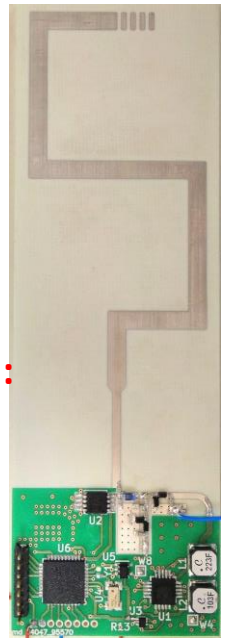
Goal: energize and localize within 15m in space battery-less tags with centimeter-level accuracy in indoor environments and read sensors

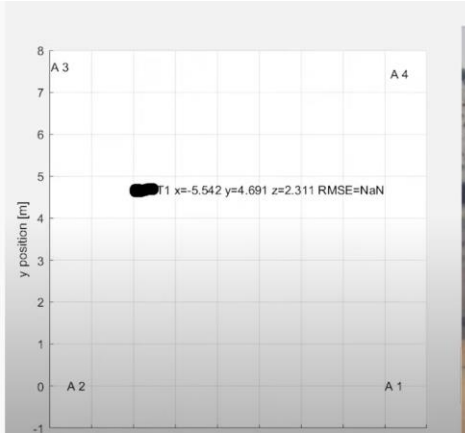


ASIC version turns on at 17m from the RF source and works until 22m



COTS version: turns on at 9.7m from RF source and works until 11m





Credits: D. Dardari, A. Costanzo, D. Masotti, D. Fabbri, N. Decarli, A. Guerra, M. Fantuzzi, M. Delprete, C. Craeye, L. Vanderdorpe, M. Droguet, T. Feuillen, D. Flandre

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IoT for energy efficiency: self-powered sensor nodes for monitoring

Efficient micro-power management circuits allow to extract tiny amounts of power and store progressively energy locally

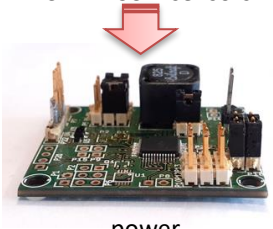
Ultra-low power MCUs and sensors allow implementation of sensor systems with sub-GHz radios operating with negligible average input power

Multidisciplinary

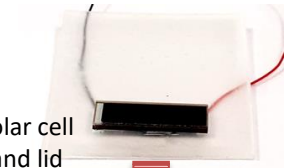
ECSEL CONNECT (ga 737434)

off-the-shelf sub-GHz radio

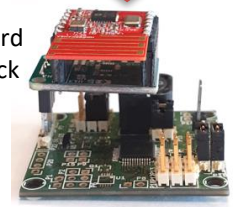
ULP MCU + sensors



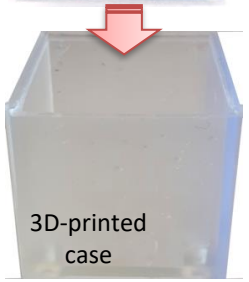
power management module with ASIC



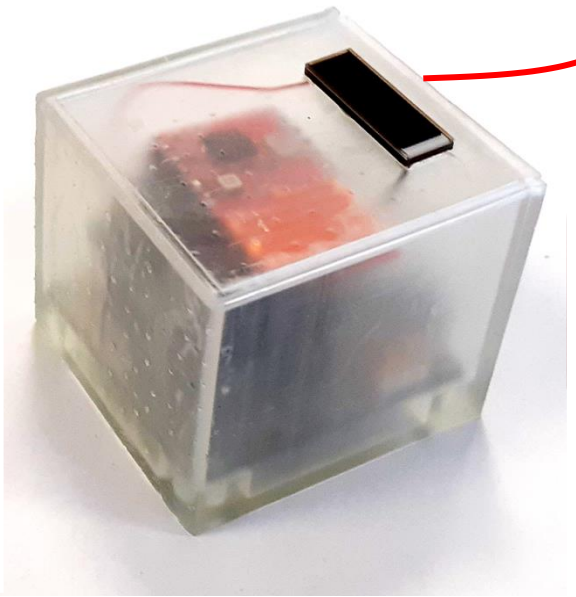
solar cell and lid



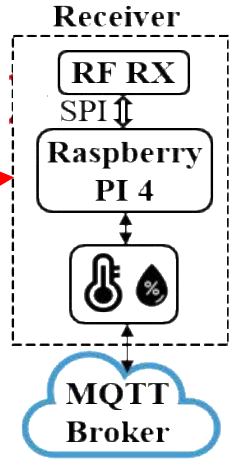
board stack



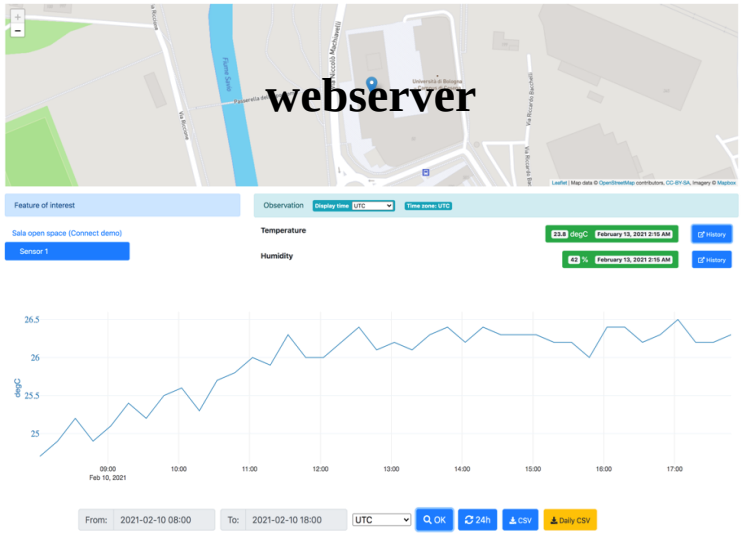
3D-printed case



sensor node (L = 4 cm)



local gateway



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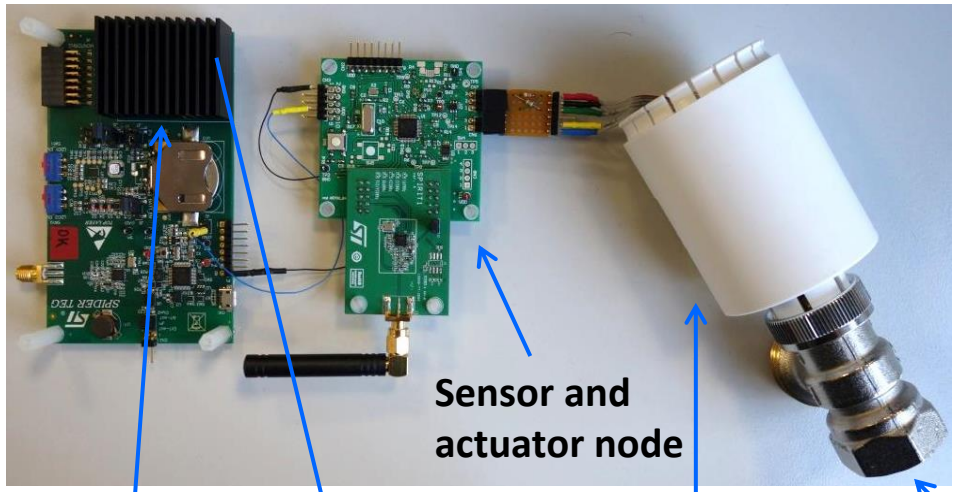
IoT for energy efficiency: Self-powered sensor/actuator node for radiator control



TEG on the bottom side

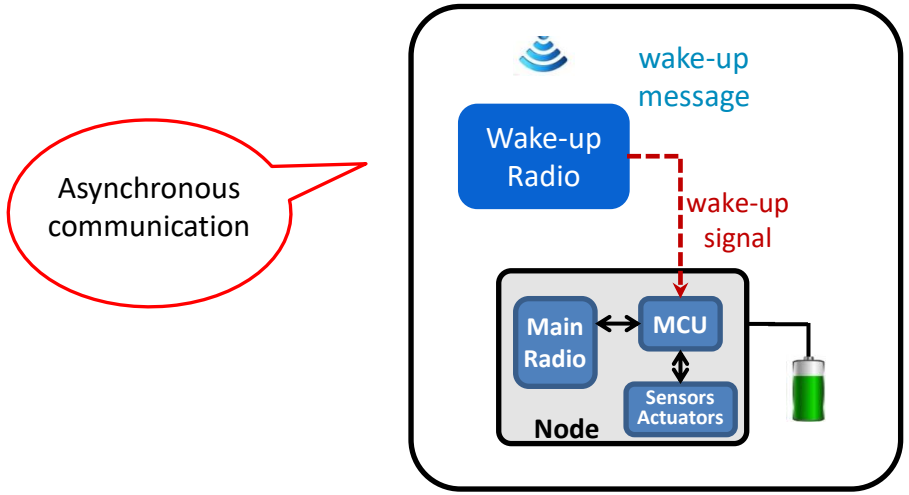
Sensor and actuator node board

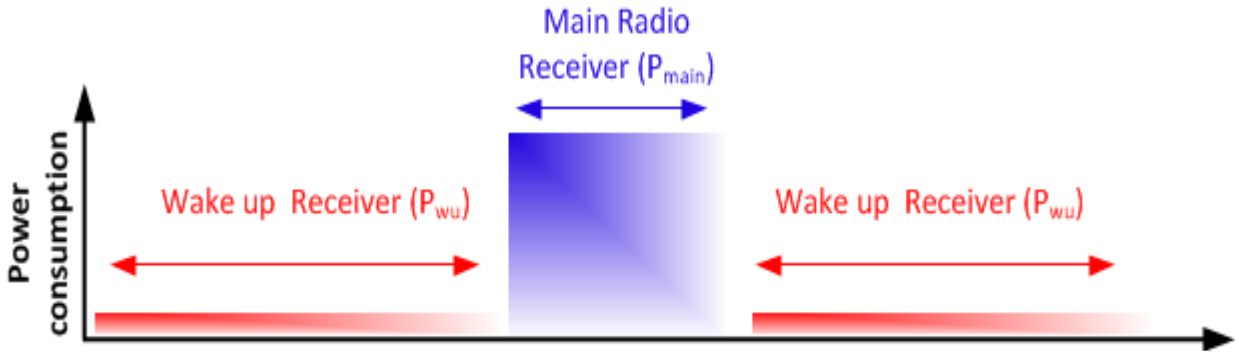
- Microcontroller (STM32L1) with DASH7 stack and real time OS (OpenTag)
- Radio and Antenna (SPIRIT1)
- Temperature sensor (STTS751)
- Low voltage motor driver (bSPIN)
- Brushed DC motor (RF-300EA) with gear box for thermostatic radiator valve control

TEG harvesting source board

- TEG (Micropelt TGP-651)
- Ultralow power Buck-boost DC/DC converter and battery charger (SPV1050)
- Rechargeable battery (LIR2450)
- Voltage regulator (STLQ015 – 2.8V)

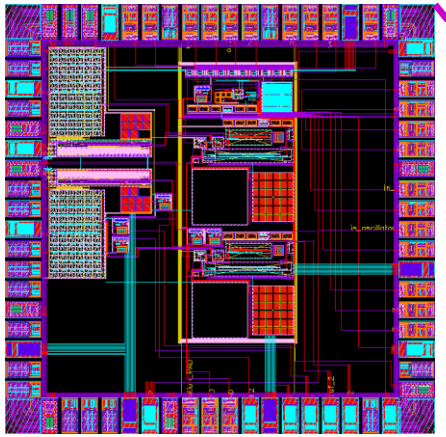
IoT for Energy Efficiency: nano-power wake-up radio receivers



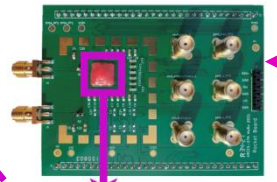


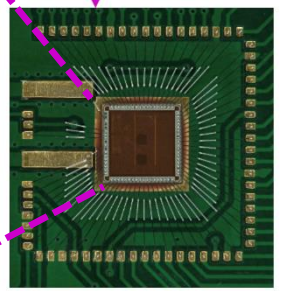
- Radio comms usually consume significant battery energy.
- Wake-up Radios are 'simpler' and energy-efficient always-on receivers used in IoT nodes to detect when a radio communication is started externally.
- When a communication is detected and a given pattern is received, WuRs turn on the main radio
- Custom integrated circuits designed in ARCES
  - Medium-Range applications (1-100 m)
  - OOK modulation, Sub-GHz ISM band carrier frequency, 1-kbps bitrate
  - Power consumption: **54.8 nW**
- **Estimated battery lifetime increase of a typical IoT node up to 5x**

Custom ASIC



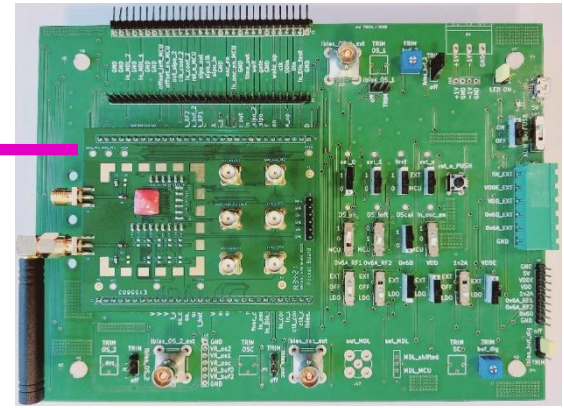
Daughterboard





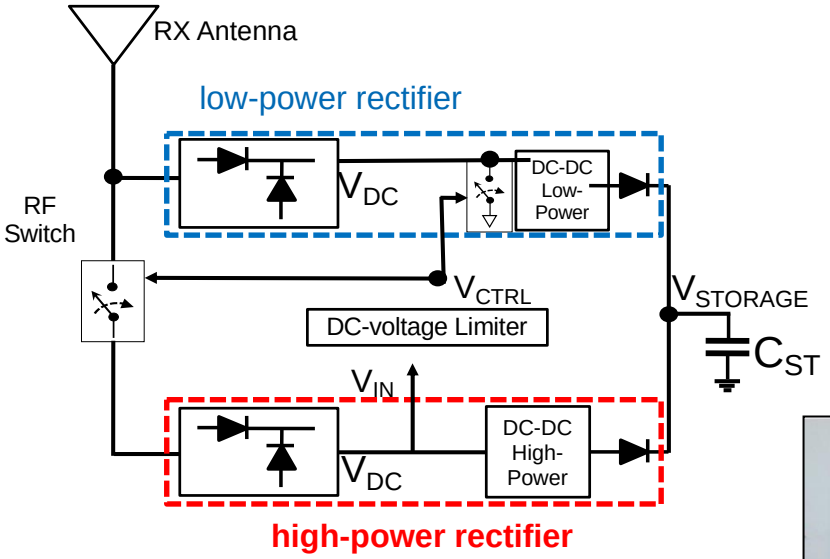
Chip-on-Board (CoB)

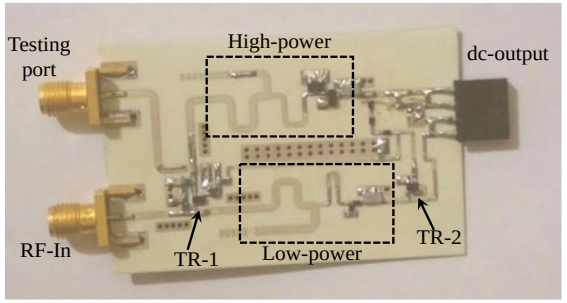
Motherboard



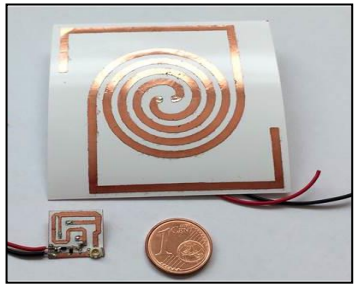
RF Design and Wireless Power Transfer

Antennas and RF circuits are essential parts of smart systems



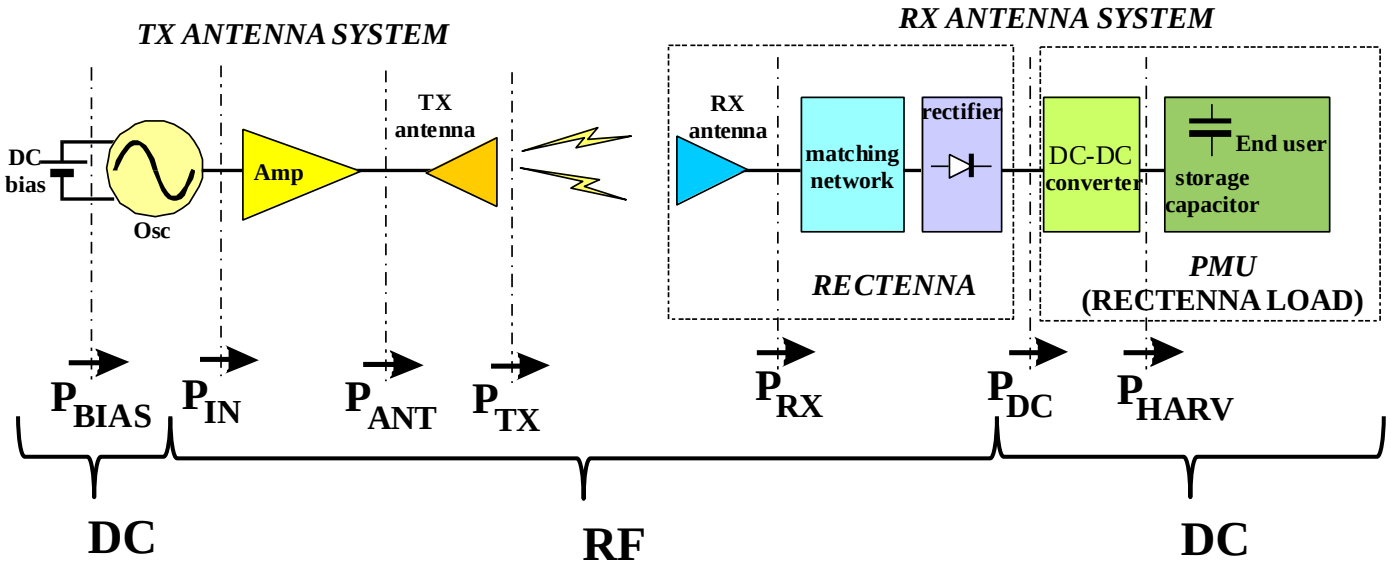


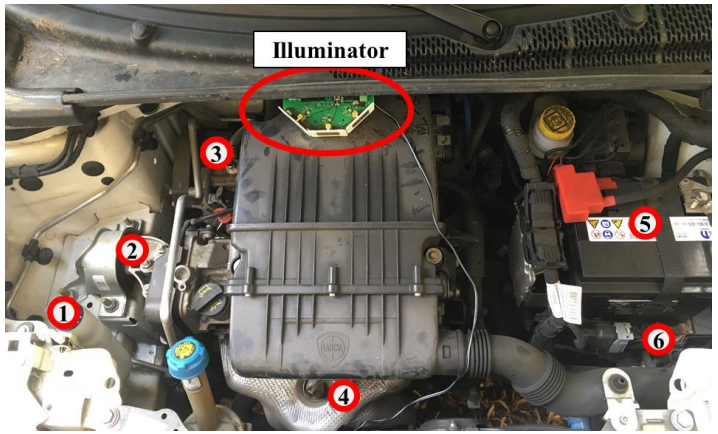
High dynamic range rectifiers

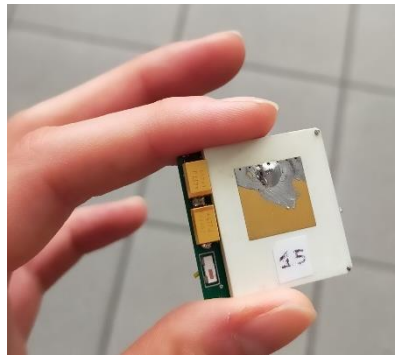


Combination of UHF and UWB antennas on paper

Far-field Wireless Power Transfer







Battery-less LoRa Nodes Operating in a Car Engine Compartment

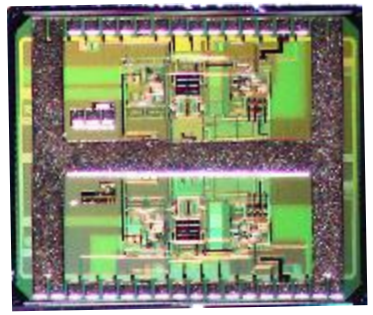
Sensors – Integrated circuit implementations

Hall-effect current sensors. High-bandwidth current sensing is crucial for many energy-related applications such as high-frequency power converters, smart meters and non-invasive load monitoring. Wideband current sensors based on Hall effect allow for the design of “smart” power electronics, where the current sensing is integrated directly in the power chip. 10+ MHz bandwidth achieved.

0.18 µm BCD technology with copper RDL strip for current sensing.

1 MHz front-end with novel octagonal-shape Hall sensor.

Cross-coupled Hall element for stress-induced offset reduction

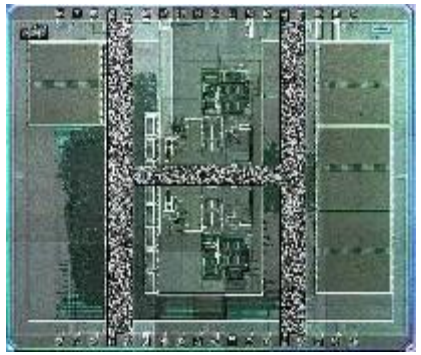


0.18 µm BCD technology with copper RDL strip for current sensing.

1 MHz front-end with novel octagonal-shape Hall sensor.

Cross-coupled Hall element for stress-induced offset reduction.

Integrated DCSE for data compression and energy-efficient data recording.



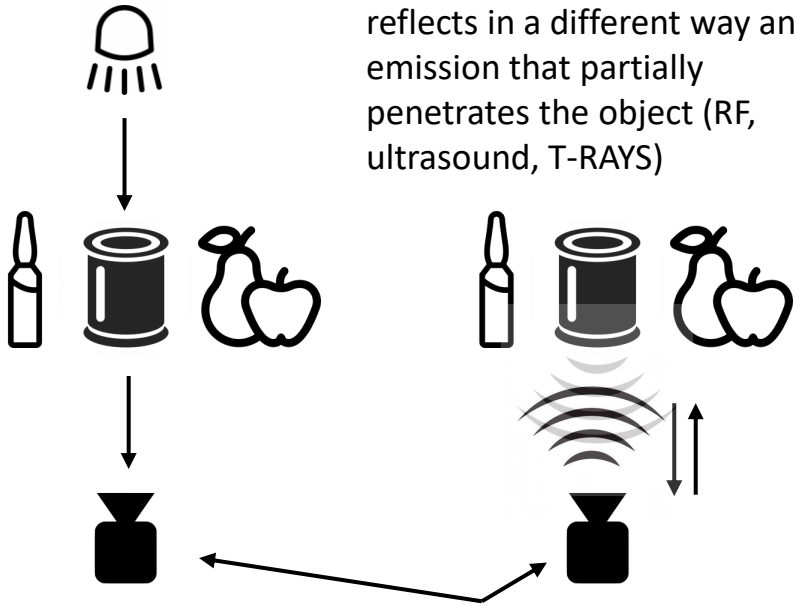
Prototype full-characterization

- *Static characteristic:*
  gain=42.5 mV/A; INL<1%; offset<180 µT;
- *Dynamic characteristic:*
  BW>1 MHz; THD<-40 dB; noise<140 µTrms (@ 1 MHz)
- *DCSE performance:*
  CF up to 128; 50% power reduction; SRER>12 dB
- *Power path impedance*
- *Temperature effects*
- *Inductive coupling*

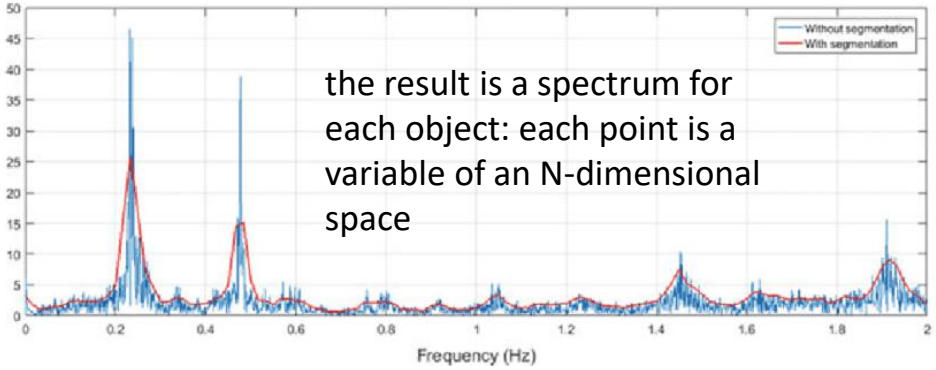
Sensors – Spectral Analysis Approach

case where the material reflects in a different way an emission that partially penetrates the object (RF, ultrasound, T-RAYS)

case where the material is transparent to EM (infra-red, RF, etc.)



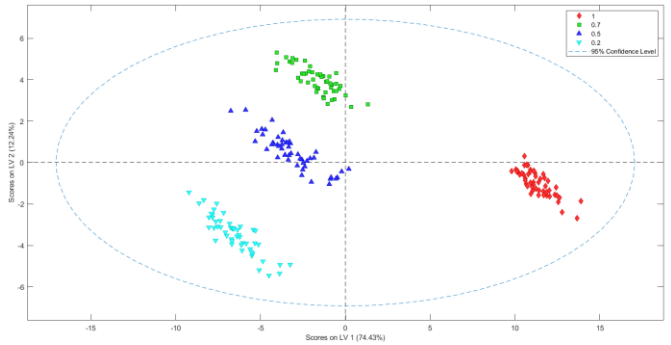
spectrum receiver (not necessarily a camera)



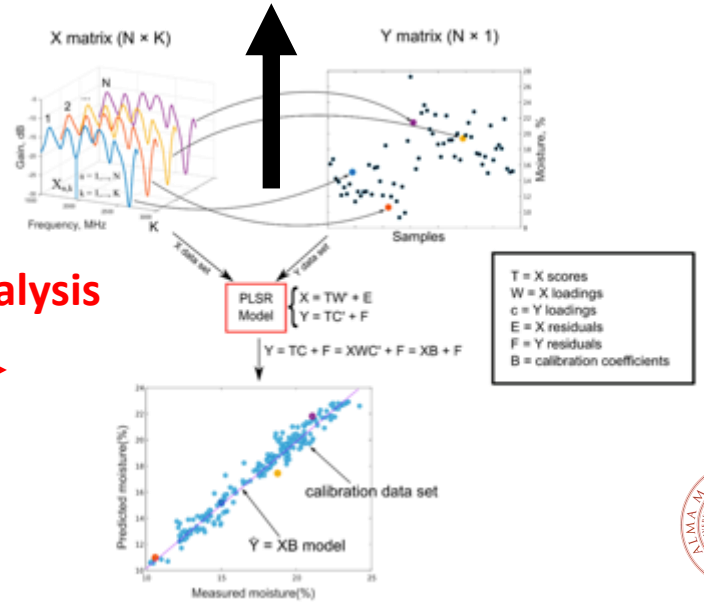
the result is a spectrum for each object: each point is a variable of an N-dimensional space

multivariate analysis

Spectrometry allows us to go beyond what is the analysis of the classical image where we can only identify the position and shape of the objects

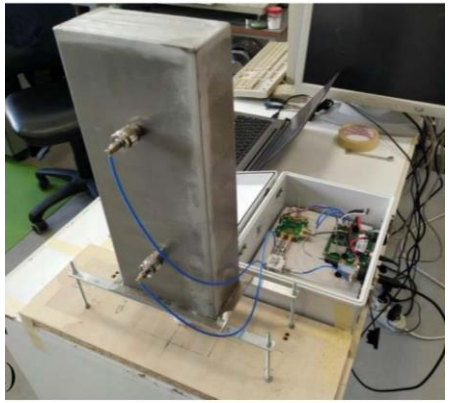


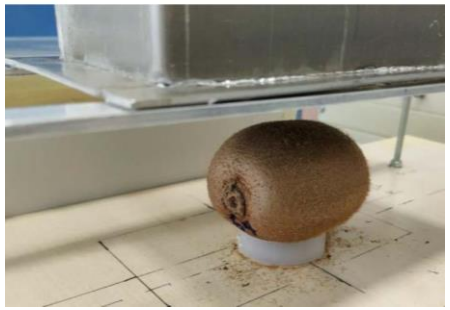
Classification on predictive model



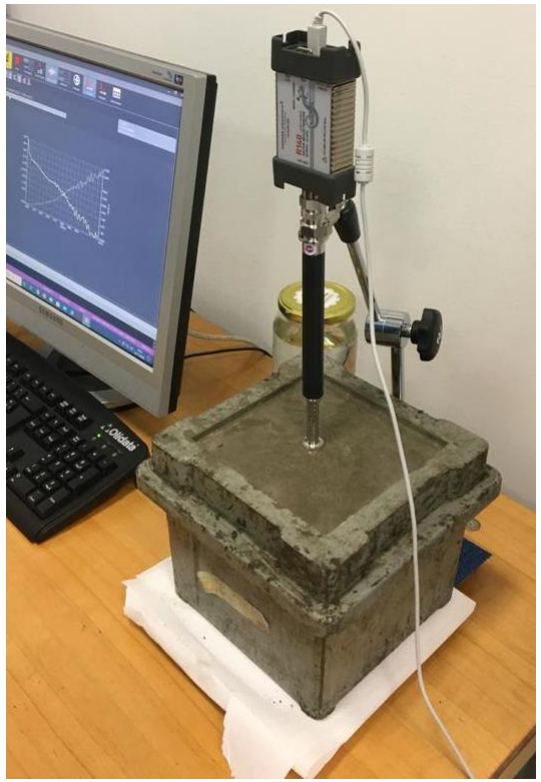
Sensors – Predictive Models

Spectroscopy + multivariate analysis: very flexible and powerful technique

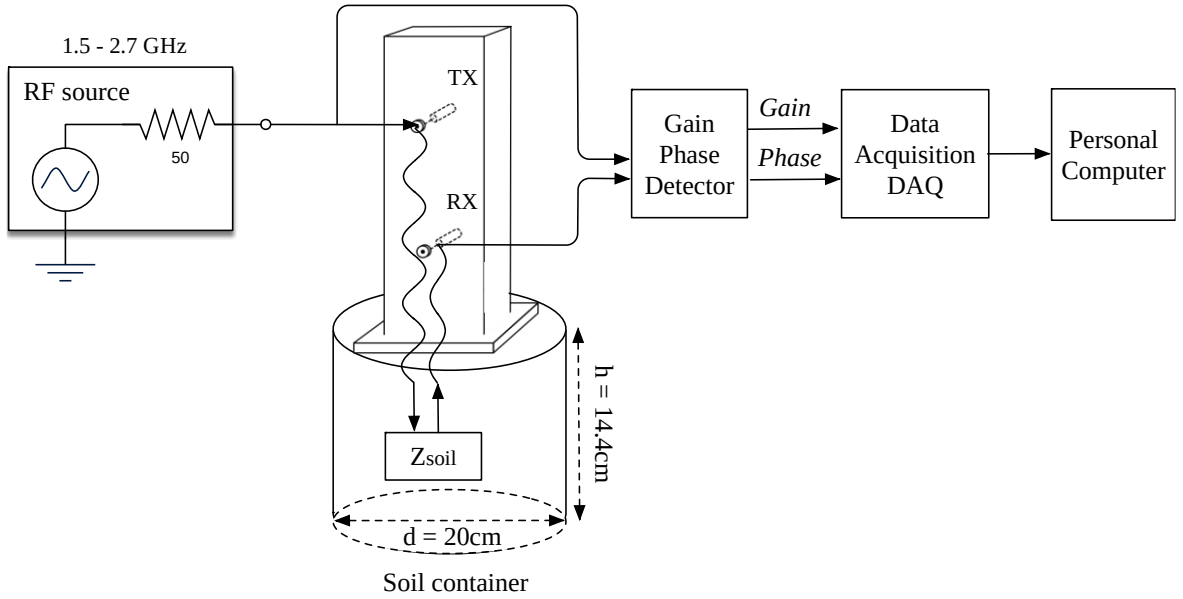




Contactless RF spectra sensor for kiwifruit firmness



Concrete hardening RF sensor



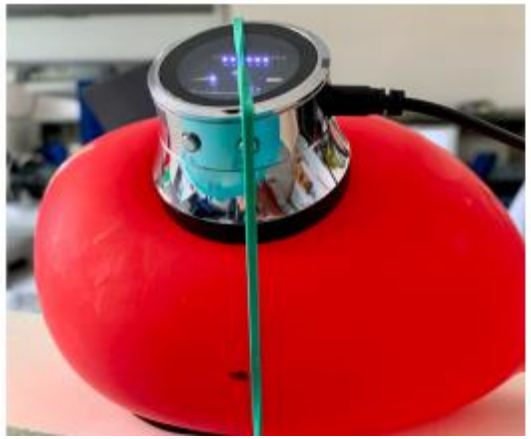
Soil container

An open-ended RF waveguide measures reflected waves from soil (no calibration is needed!) in a spectrum and analyzes by a predictive model. $R^2 = 0.989$

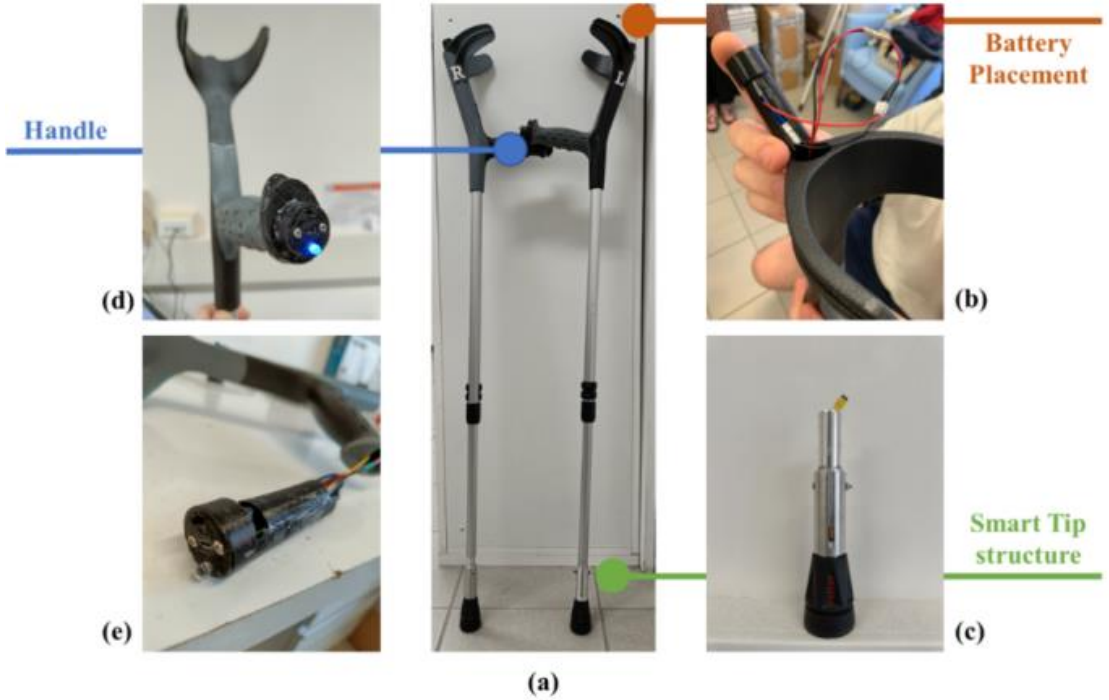
Sensors

Compact sensors (co)developed at ARCES

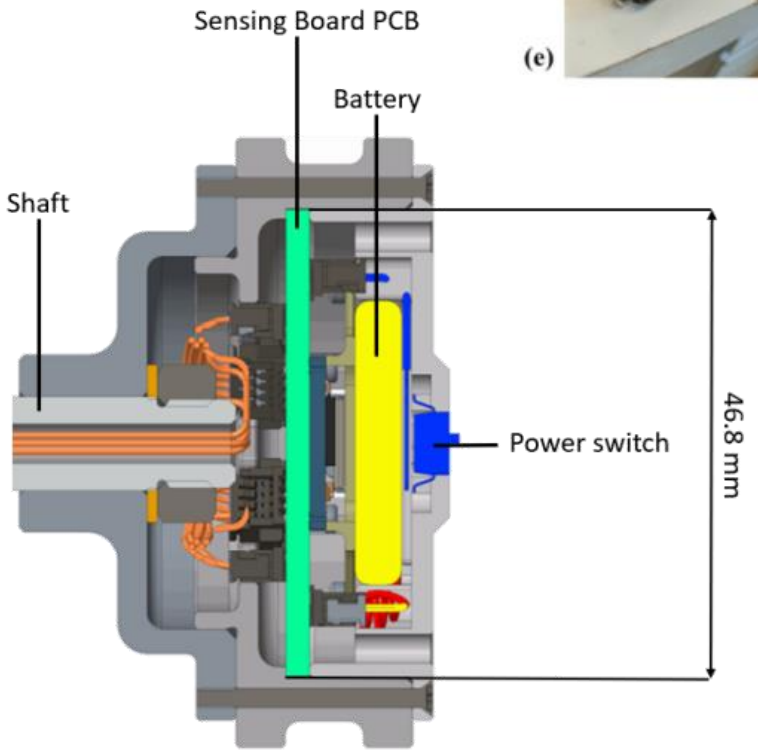
Dentrometer



Smart Auscultimeter



Smart Crutch



eMotor- embedded temperature sensing

Current/recent competitive funding on circuits and systems

EnABLES: European Infrastructure Powering the Internet of Things (H2020)

R3-PowerUP: 300mm Pilot Line for Smart Power and Power Discretes (H2020, JTI-ECSEL)

Energy ECS: Smart and secure energy solutions for future mobility (H2020, JTI-ECSEL)

CONNECT: Innovative smart components, modules and appliances for a truly connected, efficient and secure smart grid. (H2020, JTI-ECSEL)

PROGRESSUS: Highly efficient and trustworthy components and systems for the next generation energy supply infrastructure (H2020, JTI-ECSEL)

CONVERGENCE: Frictionless Energy Efficient Convergent Wearables For Healthcare and Lifestyle Applications (FLAG-ERA)

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Thanks for your attention

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