Team GRANIT

Green Radio and Adaptive Nodes for the Internet of Things

Lannion

Activity Report

2023

1 Team

Name	Forename	Position
Berder	Olivier	Full Professor, UR1 (IUT Lannion)
Carquin	Émilie	Research Assistant, UR1 (ENSSAT Lannion)
Courtay	Antoine	Associate Professor, UR1 (ENSSAT Lannion)
Gautier	Matthieu	Associate Professor (HDR), UR1 (IUT Lannion)
Gerzaguet	Robin	Associate Professor, UR1 (ENSSAT Lannion)
Le Gentil	Mickaël	Research Engineer, UR1 (ENSSAT Lannion)
Rocher	Romuald	Associate Professor, UR1 (IUT Lannion)
Scalart	Pascal	Full Professor, UR1 (ENSSAT Lannion)
Thépault	Joëlle	Research Assistant, UR1 (ENSSAT Lannion)
Vrigneau	Baptiste	Associate Professor, UR1 (IUT Lannion)

Table 1: GRANIT permanent members

The GRANIT team comprizes 8 permanent research members: 2 full professors (*Professeur des Universités*), 5 associate professors (*Maître de conférences*) and 1 research engineer. There are currently 8 PhD students in the GRANIT team. Table 1 lists the permanent staff and table 2 the current PhD students and other staff.

Name	Forename	Status	Period
Courjault	Jules	PhD	Since 06/2020
El Rhaz	Samir	PhD	Since 10/2020
Argote Aguilar	Jesus	PhD	Since 10/2021
Chillet	Alice	PhD	Since 10/2021
Balti	Nidhal	PhD	Since 02/2022
Bouro	Souébou	PhD	Since 10/2022
Muller	Thomas	PhD	Since 10/2022
Chevalier	Dylan	PhD	Since 10/2022
Lounes	Gaëtan	PhD	Since 04/2023
Bothereau	Emma	PhD	Since 10/2023
Bazerque	Paul	Research Engineer	Since 06/2023

Table 2: GRANIT other staff

2 Overall Objectives

2.1 Overview

General purpose wireless devices as smartphones already have to carry more and more data while keeping their autonomy as long as possible, but the next challenge they will face is the ubiquity of users. This ability to be connected everywhere in a continuous and transparent way, keeping the same quality of services (QoS) whatever the environment, implies that devices can deal with different wireless standards, furthermore choosing for each of them the most energy efficient configuration. In this connected world, even the smallest sensors will be able to send their data over what is called Internet of Things (IoT), such that every user in the world could reach it. The problem that designers will face is then the autonomy of such sensors, since radio is very energy consuming, and obviously, the more sensors we place, the less we want to change batteries.

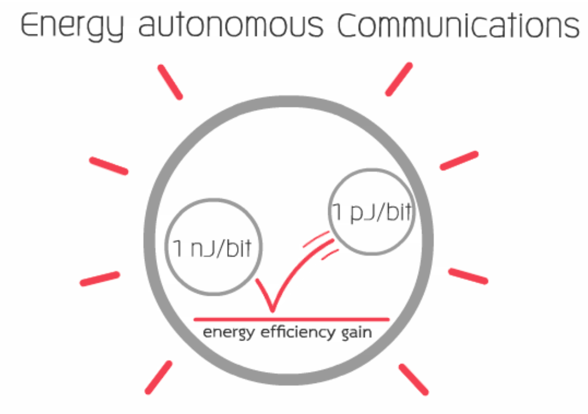

Figure 1: Transmission Energy efficiency target for the next decade

In such a context, the GRANIT team purpose is to design algorithms and architectures able to adapt to environment parameters, such as propagation channel characteristics, wireless traffic conditions network topology or possibilities of energy harvesting, while respecting applications requirements in terms of data rate, reliability, latency, and most of all, life time of involved systems, etc. As represented by Fig. 1, the quantitative target of GRANIT over the next ten years is to decrease the energy of radio transmission by several orders of magnitude to reach 1 pJ per bit. The GRANIT members have a strong experience on wireless sensor network (WSN) protocols (MAC and PHY layers) and hardware architectures, and developed several WSN platforms and demonstrators for various areas monitoring applications or dedicated to human body. As energy can now be scavenged from the direct environment of sensor nodes (light, heat, vibrations, etc.), a harvesting board can be added to WSN platforms. One of the objectives of the GRANIT team is then to design power management strategies, coupled to above-mentioned adaptive algorithms in order to reach real energy autonomy of the sensor nodes. Cooperation between nodes, either through distributed computing to find the best radio/computation trade-off or through the choice of the best cooperative relaying schemes, represents also a key challenge for the design of energy-efficient wireless systems. The GRANIT team will continue to investigate this very promising field at both physical and medium access layers. Last but not least, the aim of GRANIT team is also to efficiently implement these algorithms onto different targets, from low power microcontrollers and/or low power FPGAs for WSN solutions to powerful system-on-chip and multi-core systems for more computing-intensive applications. To answer the demand of agile devices, software defined radio solutions (SDR) will especially be considered, not only for high data-rate mobile standards such as 5G, but also for wireless sensor networks, enabling testbeds for low power adaptive and/or cooperative solutions.

2.2 Key Issues

Wireless communications represent obviously the major domain of applications for the adaptive algorithms and/or architectures proposed by the GRANIT team. The range of devices that fall within this denomination is however very large, and our developments will mainly address two different targets, namely next generations of wireless sytems (5G, beyond 5G. . .) and wireless sensor networks. In addition to analytical derivations and simulations, the GRANIT team clearly aims at using platforms to evaluate our research performance, but also to reach what could be called a platform-based design, meaning that the constraints of the envisaged platforms are taken into account very soon in the design process. Upon this basis, the research topics of the GRANIT team can be represented as Figure 2.

Focusing on the baseband processing of the physical layer, two main issues are raised by the new requirements of wireless communications: (i) What are the signal processing techniques that could help improving the link quality, the spectrum usage and the energy efficiency? (ii) What kind of hardware could associate energy efficiency and high-performance computing of these signal processing techniques? A huge effort is currently spent on proposing new physical layers and many digital communication techniques have been widely studied.

Taking into account the specificities of the targets envisaged for the adaptive algorithms, we will adapt the latter to design very energy-efficient wireless transmissions. To a certain degree, we claim that software-based systems will provide the flexibility to adapt to new requirements and make it easier to introduce innovation in the architecture[1]. Thus, our proposal relies on high-level synthesis (HLS) in order to bridge the gap between high-level specifications and hardware implementation[2]. Depending on the hardware target, hardware/software partitioning, reconfiguration capability or power management will be included in the design flow.

The objective of GRANIT members is mainly twofold, firstly confirm their expertise on IoT core technologies while exploring further the possibility to implement as close as possible application algorithms on hardware targets, secondly to take profit of heterogeneity of emerging software radio solutions to define new partitioning methodologies and address security and of course energy issues. As illustrated by Fig. 2, energy efficiency remains the principal concern

[1] J.F. Jondral, Software-defined radio: basics and evolution to cognitive radio. *EURASIP J. Wireless Commun. Netw.*, 2005, pp. 275-283

[2] P. Coussy, D. Gajski, M. Meredith, A. Takach, An Introduction to High-Level Synthesis, *IEEE Design & Test of Computers*, 26 (4): 8-17, 2009

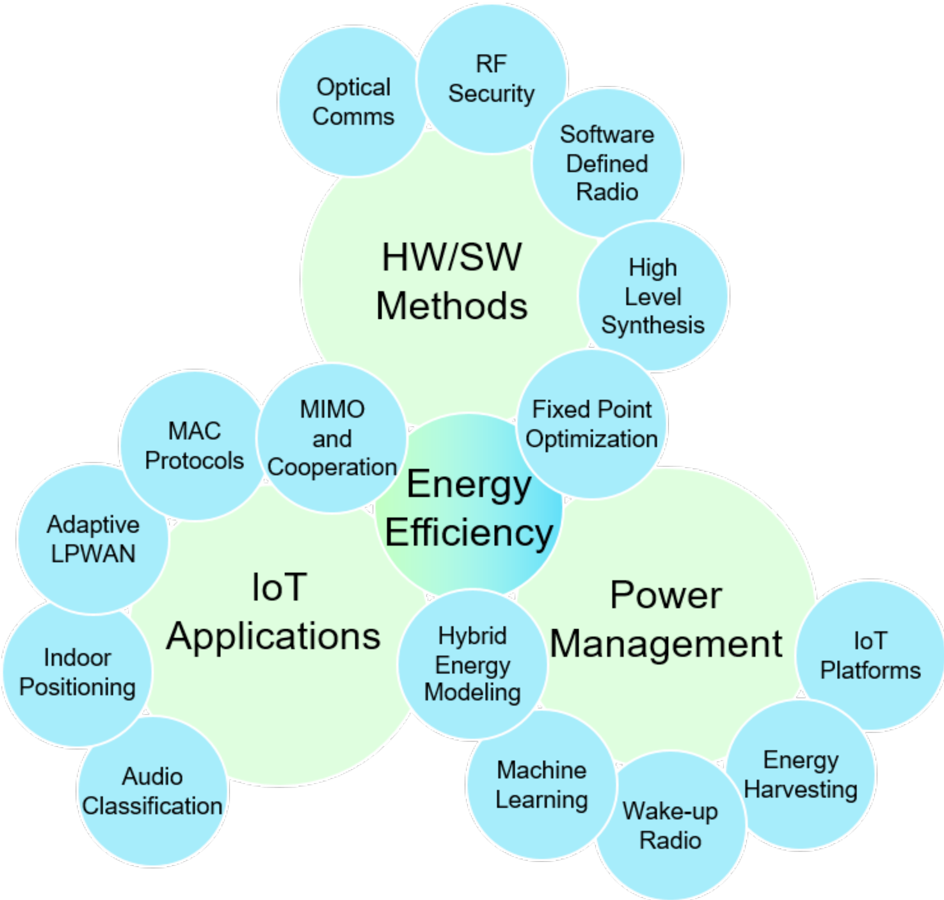

Figure 2: GRANIT Research Topics

of the team, and will be the common denominator of most of the envisioned research. This concern will feed three main topics, namely Power management, Hardware/Software (HW/SW) methods and IoT Applications. Albeit being different and complementary, the intersection between them is far from null and most of the conducted researches will be of course related to several topics.

3 Scientific Foundations

3.1 Positioning in Architecture Department of IRISA

GRANIT belongs to D3 department of IRISA dedicated to Architecture and takes place besides PACAP and TARAN teams. While these latter teams aim to design new architectures and associated compiling tools, the approach of GRANIT is more user or application-centric, i.e. our research will mostly rely on existing hardware components (even though some specific designs will still be achieved) and take into account the constraints that they incur to develop efficient algorithms. This interaction between architecture and algorithms is explored from both angles of adaptivity and cooperation.

3.2 Power management

One of the purposes of the GRANIT team is to consider algorithmic-level optimizations for energy savings. More precisely, the relationship between computation and communication will be studied from the energy point of view, in order to enable dynamic energy management. Reducing power due to radio communications can be achieved by two complementary main objectives: (i) to minimize the output transmit power while maintaining sufficient wireless link quality and (ii) to minimize useless wake-up and channel hearing while still being reactive. For this purpose, this project aims at defining and implementing new power-aware techniques that can dynamically adapt at run-time:

- the chosen algorithms of the radio physical layer (e.g. modulation, spreading, bit-rate, cooperative strategies, etc.),
- the wake-up interval of the MAC protocol,
- the accuracy (bit-width) of signal processing algorithms,
- the transmit power,

depending on some parameters such as:

- radio channel conditions,
- quality-of-service (QoS) required by the application,
- harvested energy,
- topology of the networks.

The global framework of such an optimization can be represented as in Figure 3.

The first research topic therefore directly concerns power management strategies, which aims either at decreasing as much as possible the energy consumption of wireless systems (thus increasing the latter lifetime) or at using available energy as good as possible in case of energy harvesting. GRANIT team has acquired a renowned expertise in the latter case and proposed many power managers, first for periodic sources and recently for model-free cases. However, there are still many approaches to explore to propose new energy management strategies. The first step is to elaborate accurate models, using both experiments and benchmarks to feed analytical derivations, leading to what we call Hybrid Energy Modelling. If the methodology is quite generic, the obtained model relies on the IoT technology itself, which needs a strong expertise on IoT standards and platforms. The design of the latter is one of the specificities of GRANIT since the team has designed several IoT platforms with or without energy harvesting capabilities, and we really want to continue to go until this hardware design and/or integration step to validate all our algorithms. It has to be mentioned that thanks to industrial collaborations and collaborative projects, GRANIT has benefited for five years from

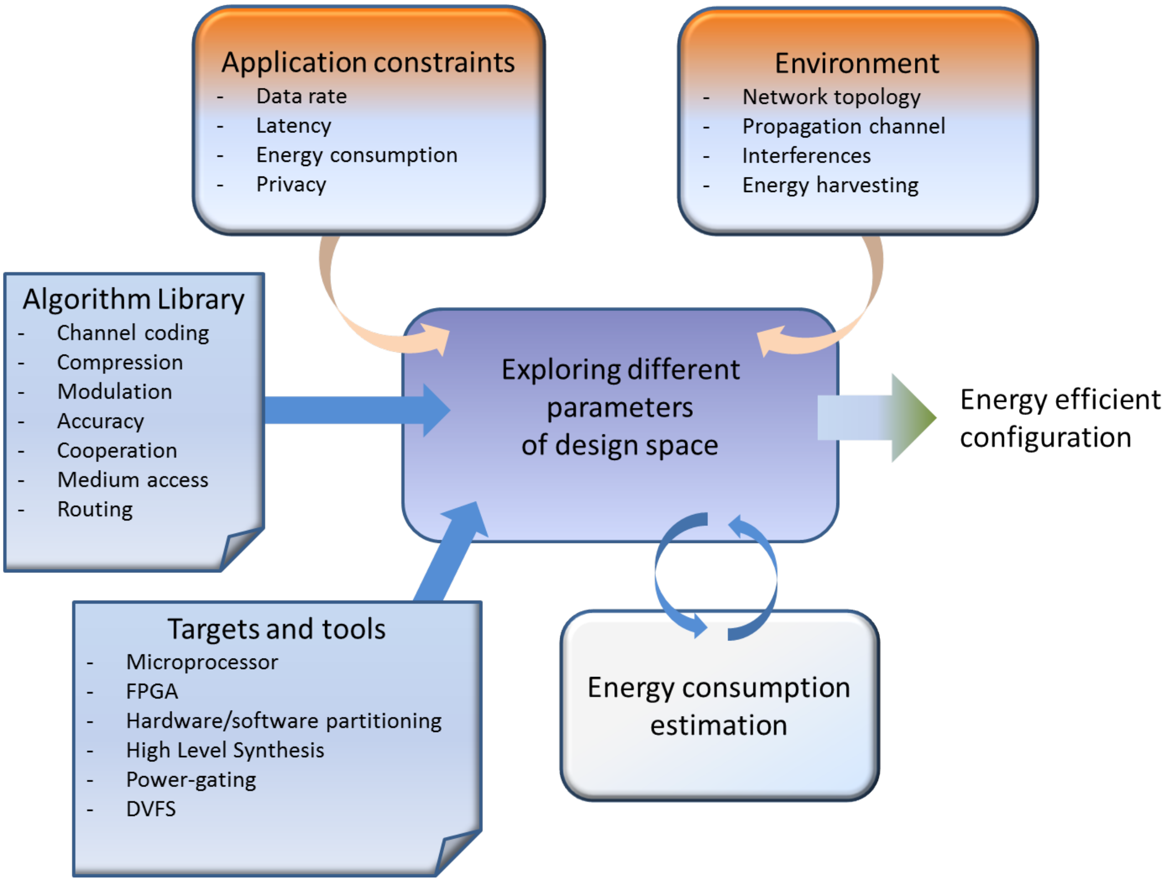

Figure 3: GRANIT Optimization Methodology

the support of several engineers that help researchers to maintain and design the platforms. This development team is shared with TARAN team, is composed of four engineers in average, and is an asset for both teams that we absolutely want to preserve. The recent development of energy efficient wake-up radios makes possible the continuous listening of wireless channels, decreasing simultaneously energy consumption and latency. But all existing wake-up radios are very application-specific and are not able to adapt themselves and find the best trade-off between energy consumption, range and latency in case of varying conditions. One of the directions we want to explore is to design smart and adaptive wake-up radios at both hardware and software levels, e.g. using light channel coding, soft decoding of addresses, adaptive preamble lengths…Finally yet importantly, it is not possible to avoid the investigation of machine learning for energy management. In previous works, we have shown the efficiency of reinforcement learning for energy harvesting nodes, but this has to be confirmed in industrial deployments with severe constraints. Machine learning is also very promising to help to adapt parameters at both physical layer (modulation, coding, spreading) and access layer (power allocation, wake-up interval…), but the overhead of such an optimization framework has to be carefully studied.

Energy harvesting Advancements in renewable energy sources, such as solar, thermal or wind, are increasing the attention in autonomous Wireless Sensor Networks (WSN). Everlasting energy harvesting allows long-term operations of wireless nodes, which can extremely reduce the cost of battery charging or replacement. Moreover, it has opened a new paradigm for designing Power Managers in self-powered autonomous nodes. Instead of minimizing the consumed energy to maximize the system lifetime as in battery-powered nodes, the PM dynamically adapts the consumed energy according to the fluctuations of the harvested energy, leading to Energy Neutral Operation (ENO)[3].

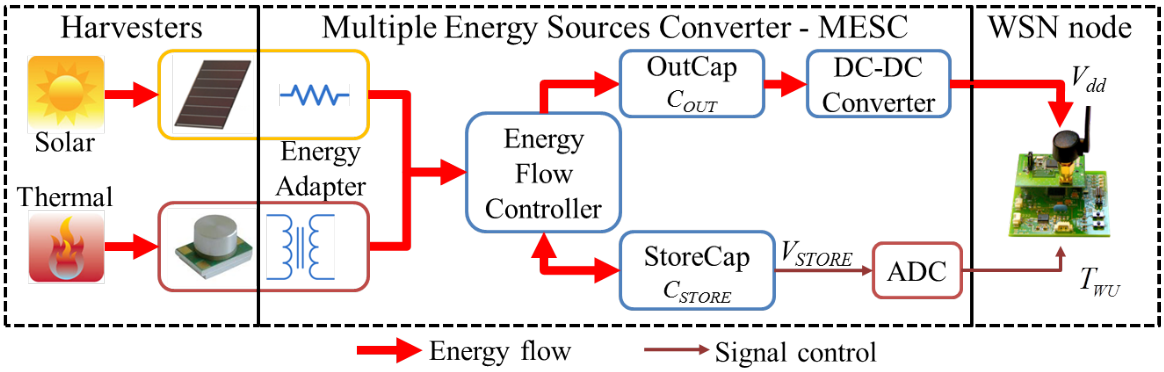

Figure 4: GRANIT Hardware Architecture of our Energy Harvesting Nodes

The GRANIT team activities in EH-WSN aim at designing and implementing new PM (Fig. 4) able to deal with the environment constraints and ensure ENO by tuning sensing, processing and communication parameters.

Wake-up radio Recently, a new consolidated technology that helps to achieve the trade-off between power consumption and latency has appeared. This technology is called Wake-up Radio (WuR). WuR is a secondary Ultra Low Power (ULP) radio subsystem that is connected to the main node. The WuR can be always on or duty cycled and its power consumption is several orders of magnitude less than that of the main node. The WuR is continuously or periodically listening to the channel while the main radio is in sleep mode, and when a specific signal called Wake-Up Beacon (WUB) is received, the WuR wakes up the main radio through an interrupt. Indeed, the WuR allows an asynchronous wake-up of the main node with a low latency. Recent circuit designs of WuR embed a decoding capability through a ULP-MCU or a correlator allowing to wake up only a specific node, thus reducing considerably the waste of energy consumption of the main radio. The fact that the WuR has an ultra low power consumption imposes hardware constraints to keep it simple. Consequently, in addition to a small bit-rate, the WuR has a low sensitivity, which induces a range mismatch between the WuR (short range in the order of 20m) and the main radio (in the order of 100m in case

[3] A. Kansal, J. Hsu, S. Zahedi, and M. B. Srivastava, Power management in energy harvesting sensor networks, *ACM Trans. Embed. Comput. Syst.*, vol. 6, no. 4, Sep. 2007

of IEEE 802.15.4). Furthermore, the robustness of the WuR presents also a bottleneck, it is very sensitive and therefore subject to noise perturbations, inducing false wake-up. Taking profit of the micro-controller embedded in the WuR (or further hardware modifications, e.g. external ADC), GRANIT team will explore various possibilities to make the WuR smarter. Furthermore, novel MAC protocols leveraging a heterogeneous network architecture composed of both long-range and ultra low power short-range WuRs have to be envisioned.

3.3 Hardware/Software methods

The second topic aims at defining tools and methodologies for efficient implementation of digital communications and signal processing algorithms. Most of emerging processing platforms, even those dedicated to low power applications for IoT, are indeed heterogeneous and composed of several processing units, that can be either dedicated to some resource hungry processing, fully or partly reconfigurable or general purpose. However, very few methodologies exist yet to take profit of this heterogeneity and efficiently partition processing over hardware or software resources. One key leveraging point is to have a unified methodology that can address different architectures with the same formalism (and the same programming language). Classic approaches are often based on low level languages (typically C or C++) to have efficient machine code at the price of the flexibility and the code concision. This is not always desirable due to the complexity of some algorithms (as most of machine learning frameworks). On the other hand, high level language (such as Python) offers a very appealing flexibility at the price of the performance... which often leads to the necessity to recode low level software processing blocks. GRANIT members will pay a particular attention to Julia [BEKS17], a scientific computing language that allows concise code description (e.g. fast prototyping) with high performance (just in time (JIT) compilation using LLVM [LA04]). This methodology should be particularly suited to Software-defined radios (SDR), which have been gaining interest in the last decades. SDR is radio communication system where components that have been traditionally implemented in hardware (e.g. mixers, filters, amplifiers, modulators/demodulators, detectors, etc.) are instead implemented by means of software on a personal computer or embedded system. Some recent designs are even so small and restrained in energy that they become an appealing target for IoT applications [CLK+16], widening the initial scope of SDR applications. GRANIT, with its broadened expertise on IoT standards will be an active actor on light SDR for IoT.

Software Defined Radio Software Defined Radio (SDR) is a flexible signal processing architecture with reconfiguration capabilities that can adapt itself to various air-interfaces. It was first introduced by [4] as an underlying structure for Cognitive Radio (CR). The FPGA (Field Programmable Gate Array) technology is expected to play a key role in the development of Software Defined Radio (SDR) platforms. FPGA-based SDR is a quite old paradigm and we are fronting this challenge while leveraging the nascent High Level Synthesis tools and languages. Actually, our goal is to propose methods and tools for rapid implementation of new waveforms in the stringent flexibility paradigm. We propose a novel design flow for

[4] Joseph Mitola J. Mitola III and G. Q. Maguire, Jr., Cognitive radio: making software radios more personal, *IEEE Personal Communications Magazine*, vol. 6, nr. 4, pp. 13-18, Aug. 1999

FPGA-based SDR applications. This flow relies upon HLS principles and its entry point is a Domain-Specific Language (DSL) which partly handles the complexity of programming an FPGA and integrates SDR features. Our studies include :

- defining a Domain-Specific Language for high-level descriptions of radio waveforms,
- generating hardware description (RTL) through the automatic synthesis of the DSL,
- including design constraints in the description through Design Space Exploration of the architecture,
- allowing Dynamic Partial Reconfiguration in the design process,
- validating the design flow from testbed with developments on the GRANIT platforms for multiple standards.

RF Security Information systems are now massively integrated into both industry and administration processes. Thus, their security is matter of importance especially when considering the storing and exchange of sensitive data. Sensitive data is also called 'red' data, in opposition with the non-sensitive (or protected by encryption) 'black' data. This crucial challenge is present at multiple scales, and leads to the emergence of different security fields linked to data protection (defense protocols) and to data interception (attack protocols)

Since few years, a new threat has emerged with the detection of the red data due to unwanted phenomena. This attack is done trough an over the air interception and thus is difficult to detect. These kind of attacks (called TEMPEST attacks by the NSA) consist in detecting an hidden channel that bear the sensitive information and then decode the 'red' information . This unwanted channel may exist due to different physical phenomena such as electro-magnetic coupling, radio frequency leakages, or mechanical mechanisms.

In GRANIT team we have a strong interest on these kinds of thread among three main axis:

- We make thorough analysis on some potential security beaches on existing standards (Bluetooth, Zigbee. . .) and boards (System On Chips)
- We also conduct studies and analysis on how Software Defined Radio (SDRs) can increase the criticality of TEMPEST attacks making discrete, compact, long range interception devices handy. On this particular aspects, efficient use of SDR is of importance due the large bandwidths and the harsh real time constraints encountered.
- We investigate methods to be able to identify a transmitter only based on the distortions induced by the transmitted signal. These distortions are due to analog stages of the transmitter and are called Radio Frequency Fingerprint (RFF). The RFF can be used as a non falsifiable identifier

3.4 IoT applications

Some applications, as smart cities, connected farms or wildlife monitoring require transmission of data over long distances at a reasonable energy cost. Emerging standards known as Low Power Wide Area Networks (LP-WAN) respect these requirements by proposing trade-offs between transmission range, data rate, and energy consumption. Most of them are tunable through modulation or coding parameters, such as LoRa, and GRANIT team has acquired a highly recognized expertise on LPWAN adaptation to device environment (propagation, interference, energy harvesting...). However severe propagation constraints have still to be explored, for example for factories of the future that represent very specific environments that can vary a lot from one place to another. Indeed, the indoor environment with a lot of metallic structures and multiple reflectors may lead to severe attenuation, and specific power equipment or machine tools generate impulsive noise. In order to efficiently deploy wireless sensor nodes in factories, there is a crucial need for fast and accurate performance estimation of IoT technologies in this particular context. Based on these results, GRANIT will also explore the possibility to dynamically adapt transmission parameters thanks to reinforcement learning.

GRANIT has a historical expertise on MIMO systems, especially on precoding, whether distributed or not. Precoding aims at using the channel knowledge at the transmitter to adapt the signal to be transmitted to the propagation conditions. Widely used for cellular systems where multiple antennas are embedded on base stations (a.k.a massive MIMO) and mobile devices, precoding can also be used in a distributed and cooperative manner for small IoT nodes, and GRANIT will explore this approach in a security context. A wireless transmission is indeed naturally subject to interception (passive eavesdropping). To circumvent this and increase the secrecy of the transmission, different techniques can be used and can be greatly improved when done in a cooperative manner. In the following years, we will study on how the increasing number of antennas and how the use of precoding/beamforming strategies can improve the secrecy rate of an IoT communication link.

For most of IoT sensor nodes, the communication part is the most energy consuming, and radio activity has therefore to be reduced as much as possible, to avoid idle listening and overhearing. GRANIT will continue to explore this degree of freedom and propose adaptive MAC protocols for heterogeneous systems with several coexisting standards and technologies. For example, heterogeneous networks can be composed of LPWAN and WLAN nodes, potentially equipped with wake-up receivers, with energy harvesting capabilities... As the range and the energy autonomy of all these devices are not the same, there is a crucial need for access protocols that combine all these wireless technologies to reach the best quality of experience as possible.

Indoor positioning Among possible applications of IoT networks, let us emphasize two main topics that GRANIT members want to explore. The first one is indoor localization, useful for industry 4.0, logistics, but also museums, that all require accurate positioning (around 10 cm). In such a stringent requirement, Ultra Wide Band (UWB) based techniques have emerged as accurate solutions. Such radios combine low to medium rate communications with positioning capabilities using ranging techniques. If UWB offers outstanding accuracy, the performance significantly degrades in severe environments (multipath in crowded rooms, impulsive noise in factories). Moreover, to propose energy efficient solutions, a complete cross layer approach has to be envisaged, including hybrid algorithms combining Two Way Ranging (TWR) and Angle of Arrival (AoA) methods, as well as dedicated MAC protocols.

Audio classification The second one relates to audio processing, whether for spatialized sound transmission, in relation with localization explained hereabove, or for context recognition. More and more applications indeed need accurate context recognition to propose adequate services and acoustic sensors appear as very efficient to discriminate environments. The multiplicity of sensors in the same scene obviously enrich the information but transmitting the whole audio flux is very energy consuming. GRANIT wants to explore the possibility of deporting processing as close as possible to the sensor, which i) decreases the amount of data to be transmitted and ii) allows to guarantee a high level of privacy to users. A particular attention will be paid to the distributed implementation of convolutive neural networks. For spatialized sound transmission, no standard exists yet to transmit high quality spatialized sound with low latency, and GRANIT aims to explore with industrial partners what low power SDR can bring, eventually designing full custom systems.

4 Hardware and Software

4.1 EEWOK

EEWOK (Energy Efficient Wireless sensOr networKs) is a proteiform platform deployed and maintained by the GRANIT and TARAN team from IRISA lab. Elected Emerging Rennes 1 platform in 2022, it regroups several elements build from many years of experience in designing very low energy sensor nodes. Depending on the application, it is available in several versions that integrate the same basic elements (low-power microcontroller and several sensors) to which are added important technological innovations (low-power FPGA, energy recovery, software radios, wake-up radio, etc.). These sensor nodes are thus deployed in networks of various scales (up to several hundred nodes for Smartsense). To verify their energy efficiency, the platform has a number of measuring devices (oscilloscopes, spectrum analysers, current analysers, etc.)

PowWow platform for WSNs We have proposed and developed PowWow (Power Optimized Hardware and Software FrameWork for Wireless Motes), a hardware and software platform designed to handle sensor networks and related applications. The main innovating features of the platform are: an energy-efficient MAC protocol (15x less power than the ZigBee standard was reported for equivalent applications), a much more light memory usage, a low-power FPGA for acceleration of part of the software stack (energy reduction of two orders of magnitude was reported for error control and correction) and, more recently, a board including small-scale energy harvesting features, as illustrated on Fig. 5. Our work takes benefit from PowWow to perform power measurements that can be directly introduced in energy consumption models, leading to very precise predictions for the class of preamble sampling MAC protocols. We strongly rely on this platform for the prototyping of future research in this domain.

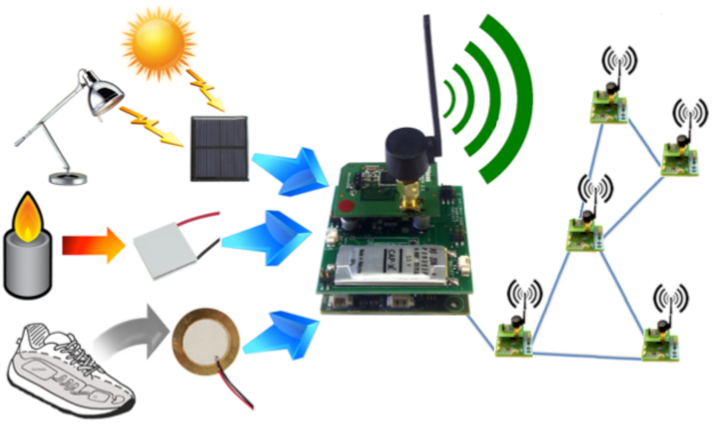

Figure 5: PowWow WSN Platform with Energy Harvesting

Energy autonomous LPWAN nodes (AMALO) The board AMALO (AutonoMous energy hArvesting LOng range) has been made as part of the collaborative project ALAMO with local companies (Europrocess and CG Wireless). The main aim of this system is to have a platform interfaced with several sensors that can harvest energy and transmit information with a long range radio module. We choose to use the LPWAN LoRa technology mainly because of its flexibility. It can be used in standalone (LoRa) or as part of a standardized protocol (LoRaWAN) with private or public network.

On the block diagram on the left of the Fig. 6, two features can be identified: Energy Harvesting and Processing. Firstly, the Energy Harvesting block is made up of the energy manager chip (SPV1050), the energy source (solar panel, Peltier module, etc.), an energy storage (a super-capacitor and/or a battery) and a chip able to measure the battery current and voltage. Secondly, the Processing block consists of the Murata CMWX1ZZABZ-078 chip and the sensors (with the click-board header and/or the buses header). Click-board header allows us to easily update sensors like temperature, humidity, motion, etc. or add new radio modules and controller. We can see the different elements of the AMALO board on the described board picture (on the right of the Fig. 6).

One of the objective of this project was also to define a methodology for sizing energy harvesting components. The proposed methodology must define both energy storage devices (i.e. sizes of battery and capacitor) and harvesting components (i.e. solar panel area) of the AMALO platform. These elements depend on QoS parameters, hardware characteristics and environmental harvesting conditions.

Wireless Body Area Networks (Zyggie) Zyggie is a motion capture platform design within the labex Cominlabs BoWI project. It consists of a set of electronic components (nodes) arranged on a part or the whole body of a person. The Inertial Measurement Unit (IMU) embedded in these nodes can duplicate the movement on an avatar moving on an Android tablet, as shown by Fig. 7. Communication between nodes is performed by radio and extensive

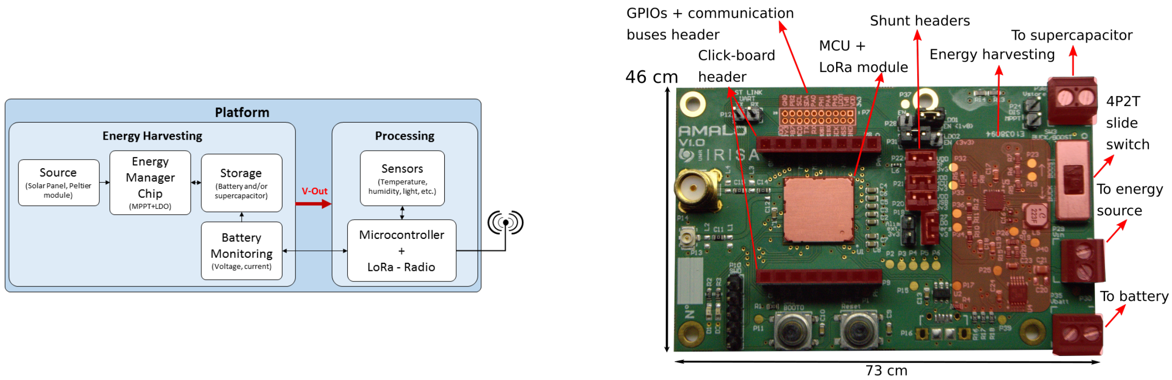

Figure 6: AMALO Block diagram (left) and described board picture (right)

energy optimization allows them an operating autonomy of 20 hours. As recharging nodes batteries also occurs wirelessly, it is therefore possible (even if this is not the case for current prototypes) to embed them in a waterproof box.

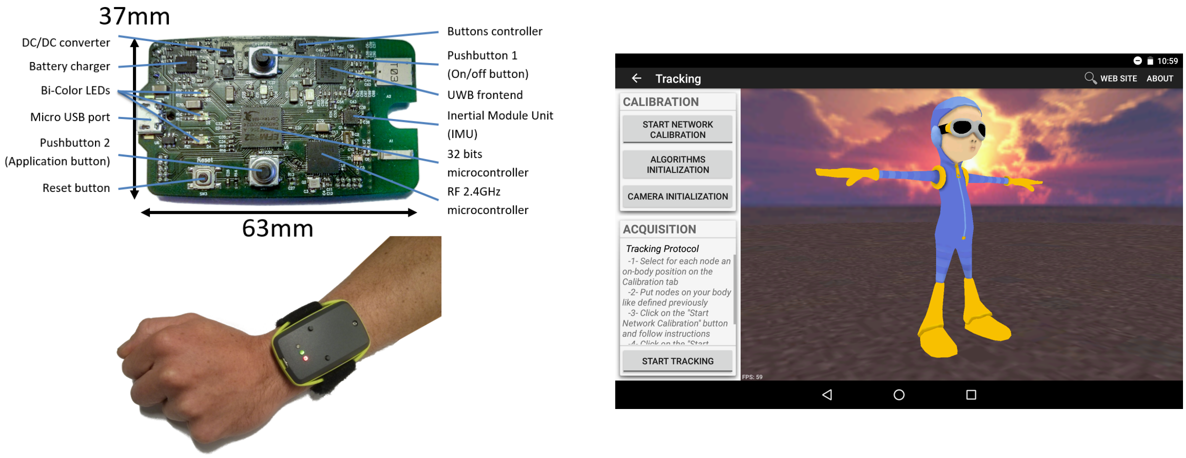

Figure 7: Zyggie V2 and avatar application

This state-of-the-art platform has enabled to thoroughly analyze BAN sensor network related challenges dedicated to motion capture. Our work focused primarily on opportunities to dispense with the energy intensive gyroscope, using radio power information received by the sensor network. The applications are animation, functional rehabilitation, optimization of sports movements, robotics, non-verbal communication in fighting situations.

A new version of this platform was recently designed with high integration constraints as shown by Fig. 8. The system embeds Bluetooth communication, new IMU with high rate data fusion and memory chip to deal with fast motion applications. A motherboard was designed to charge the battery with C-type USB connector and interface other sensors.

SDR platforms In the context of SDR paradigm, GRANIT team studies the rapid prototyping of flexible radio waveforms leveraging High Level Synthesis. Both algorithms and architec-

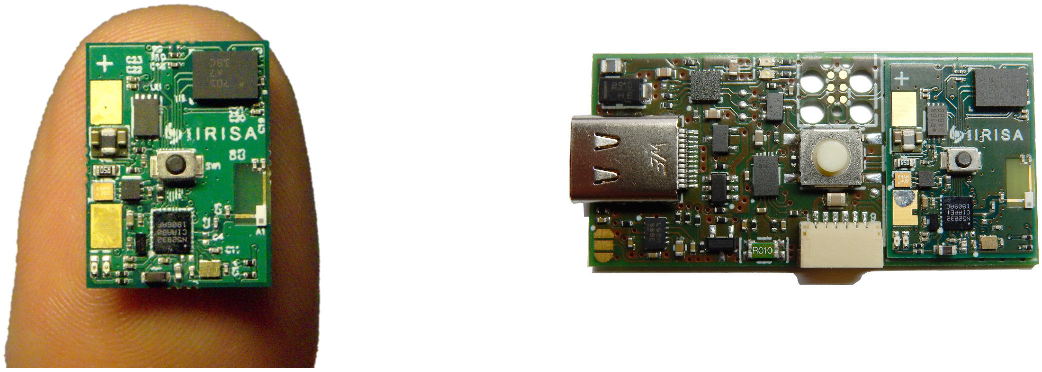

Figure 8: Zyggie Light and its motherboard

tures are taken into account to target heterogenous (software and hardware) SDR platforms. During the Equipex FIT, GRANIT members have experienced the Nutaq Perseus platform to validate our research by targeting two standards (IEEE 802.15.4 and IEEE 802.11a). We currently use Zynq-based platform from Xilinx to achieve the above mentioned heterogeneity.

The ROSE platform (Software Defined **R**adio Platform for **Io**T heterogeneou**s** **e**mbedded systems) has been deployed in 2017. The platform is composed of several USRP-310 devices from Ettus. These SDR belong to the new generation where the architecture is based on both a PS (processing system, here a dual core CPU) and a PL (programmable logic, e.g an FPGA); based on Zynq platform. The SDR platform has been partially funded by the Brittany region, the Côtes d'Armor Department Council (CD22) and the University of Rennes.

SmartSense With 150 nodes deployed in the buildings of IRISA's laboratories (Lannion and Rennes), the SmartSense platform makes it possible to collect a large amount of data on energy consumption and usage in buildings. This data allows a large number of applications, notably in data mining, disaggregation of electrical loads or processing of sensor data.

SmartSense consists in power measurements and sensor nodes (Fig. 9) :

- The power consumption can be obtained at different levels (individual, a room or whole stage) or on the types (light or plug sectors).
- Each node includes about twenty sensors: image, infrared, audio, radio spectrum, inertial unit, humidity, pressure, temperature, light (red, green, blue, white, UVA, UVB), distance radar with centimeter accuracy, CO2 and VOC (Volatile Organic Compound). A room may host several nodes for spatial diversity.

This project was funded by CPER SmartSense and currently takes place in the Equipex+ TERRA FORMA to monitor anthropized natural systems.

4.2 FICOP: Foton Irisa Common Optical Platform

To achieve the vision of a distributed, programmable and flexible infrastructure facing the ever growing data volume and the cloudification of services, there is a necessity to investigate,

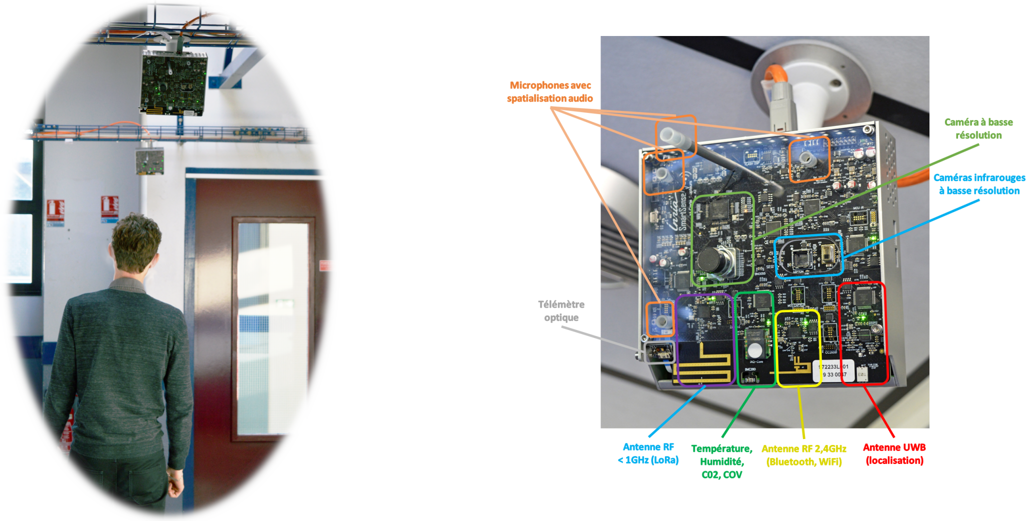

Figure 9: SmartSense network

design and experiment transport networks with high bandwidth capacity and agility for smart adaptation to application needs, based on reconfigurable optical systems controlled by software-defined networking (SDN) approaches.

To explore those issues a new optical platform was created between IRISA and Foton laboratories to merge skills of both teams, respectively on digital signal processing and optical communications. This platform was founded with CPER project and allows off-line 30GHz communication link. With 100Gsps Oscilloscope and 88GHz arbitrary waveform generator this equipment is use to design and test new algorithms to enhance next generation optical links.

5 New Results

5.1 Highlights

- Sport monitoring activities of GRANIT were emphasized at Fête de la Science, and kayak motoring activities (PhD of Souébou Bouro in collaboration with M2S and FFCK) were highlighted in several general public and popularization publications (The conversation, Sciences Ouest)

- 2023 was a great vintage for GRANIT in ANR with 3 accepted projects (Light-Swift, Perenne and OWL)

- International collaborations were also enhanced since ANR Light-Swift on Edge AI is in collaboration with NTT and NII (Japan) and UTIQUE (with ENI Tunis) was accepted as PHC by CNRS. Matthieu Gautier received a grant to be a visitor at Sherbrooke from February to August 2024. Three PhD students have spent 3 months in foreign Labs: Alice Chillet in Tampere (Finland), Jesus Aguilar Argote in Aachen (Germany), and Jules Courjault in Trento (Italy).

5.2 Software Defined Radio

Participants: Robin Gerzaguet, Matthieu Gautier, Olivier Berder.

Software Defined Radio (SDR) aims to revisit the paradigm of RF architectures. Classic RF architectures are massively integrated, hardware oriented, and can not cope with various bandwidths and carrier frequencies. SDRs are immensely popular as they allow to have a flexible approach for sounding, monitoring, or processing radio signals through the use of generic analog components and lot of digital signal processing. SDRs indeed deport the processing in a software part through the use a general purpose processor (GPP) or digital signal processor (DSP). The processing can be done with the use of high level language such as C++ and Python. This paradigm change allows to use flexible devices that are able to address a wide frequency range (typically from 100MHz to 3-6 GHz) and different services and applications.

In 2023 we have further increased our contributions in the Julia SDR ecosystem by adding new backends for SDR in AbstractSDRs allowing to efficiently use low cost high performance BladeRF from Nuand. External collaborators have also proposed enhancements for DigitalComm (package related to simulation of Physical layer) and AbstractSDRs packages.

In [11] we have proposed a real-time architecture dedicated to the interception of Bluetooth signals in order to carry out a vulnerability analysis of a side channel.

5.3 Energy Harvesting and Power Manager Design

Participants: Olivier Berder, Matthieu Gautier, Jesus Argote Aguilar.

Wireless sensor networks (WSNs) are made up of multiple wireless sensor network nodes that monitor an environment and collect data into one or more locations called sinks. These networks are a key technology in the Internet of Things (IoT) and are essential in many applications such as smart cities, smart factories or precision agriculture. To deploy large WSNs, they should be able to operate over a long period and, generally, the stumbling point of this type of application is energy. Indeed, traditional wireless nodes are supplied by individual batteries, which can only store a limited quantity of energy. Using harvesting energy to power WSN devices is an appropriate solution to reduce the dependency on conventional sources (e.g. batteries).

Nowadays, the efficiency of Radio Frequency (RF) energy harvesting circuits is continuously increasing and, at the same time, the energy consumption of connected devices is drastically decreasing. Despite that, collecting, storing and delivering such kind of harvested energy to the device in an appropriate manner is still a challenge.

Moreover, providing a regulated DC voltage from low RF power is a challenging task. In [2, 4, 3], we present a low-input-power RF harvester designed with off-the-shelf components and composed of an RF rectifier and a power management integrated circuit (PMIC). In the rectifier, an inductive-matching technique is employed which consists of an inductive branch composed of a lumped inductor together with a short-circuited stub due to sub-GHz frequency. The rectifier is designed to present an optimal DC load in function of the PMIC operation at low powers. Measured RF-to-DC conversion efficiency of 32% and DC output voltage of 186mV with an input power of -20 dBm at 888.7 MHz are achieved in the rectifier. Measured peak efficiency is 52% at -4 dBm. At -20 dBm, a relatively high efficiency and output DC voltage are obtained compared to other discrete rectifiers. For this power level, this performance is sufficient to maintain the operation of the PMIC that delivers a power of 324nW aiming to supply an ultra-low-power wake-up receiver. The required RF power to deliver a regulated DC voltage is so far the lowest reported in the literature for an RF harvester using off-the-shelf components and a continuous wave (CW) signal to date.

5.4 Wake-up radio

Participants: Olivier Berder, Antoine Courtay, Matthieu Gautier, Nour Djidi, Clement Caresmel.

Wake-up Radios (WuRs) represent one of the most promising solutions for allowing an ultra-low power consumption in wireless sensor networks. For instance, they could help reducing the energy wasted during connecting and control processes. This is specially the case in the neighborhood discovery process that is performed in Bluetooth Low Energy (BLE) before communications between devices. The fixed duration of this process has an important energy cost when the number of neighbors is low or when only few neighbors are required by the application. To tackle this issue, a novel protocol, WUBBLE, is proposed in [10] that leverages wake-up radio technology to both start and end the discovery process. Wake-up radio enables additional communications between devices with an ultra-low energy overhead. WUBBLE is validated by combining analytical analysis and experimental measurements and results show that half of the energy could be gained to discover 90% of the neighbors.

5.5 Long range communications performance

Participants: Olivier Berder, Baptiste Vrigneau, Jules Courjault.

Low Power Wide Area Networks (LPWAN) are very promising for a variety of IoT applications, but they face two major challenges: energy consumption of the wireless nodes and congestion of the networks due to the huge number of nodes involved. LPWAN transmission parameters can be optimised, e.g. using artificial intelligence algorithms, but the performance estimation made during simulations is often higher than what it is in reality. In [8] and [9], we propose a new LoRa network simulator, J-LoRaNeS. Based on the Julia programming language, it allows fast prototyping and is therefore suited to the study of different adaptive LoRa mechanisms. We used our novel simulator to clearly show the benefits of using multi-arm bandits for adaptation, but we also show that the benefits reported in the literature are not attainable when realistic network conditions are simulated.

5.6 Radio-Frequency security

Participants: Olivier Berder, Robin Gerzaguet, Matthieu Gautier, Corentin Lavaud, Alice Chillet.

In modern computing architectures, sensitive data (*red data*) is carried out in the same processing units as encrypted data (*black data*). Due to internal mixing or coupling, this red data can be emitted in a legitimate radio transmission through a so-called telecom side-channel. The work described in [11] falls within the framework of "TEMPEST telecom," where a legitimate signal carrying information is coupled with a compromise, mainly a narrowband one (audio signal, encryption key, . . .). We focus on Bluetooth systems whose physical layer based on frequency hopping makes the detection and exploitation of this hidden channel more complex. As the hop sequence is unknown by the receiver performing the analysis, we describe a real-time hardware architecture based on software-defined radio. This architecture is capable of detecting the used Bluetooth channel and extracting the vulnerability. Finally, we reveal a vulnerability on an nRF52832 System On Chip where a signal from an internal PWM is extracted via reception of the transmitted Bluetooth signal.

Furthermore, we have a strong interest in device identification. In the latter work, we have demonstrated that System On Chips may exhibit signal compromission. Practical eavesdrops are however difficult as several devices may transmit data in the same time/frequency resource. As a consequence, GRANIT team has initiated works on identification based on Radio Frequency Fingerprint (RFF). RFF is a unique signature created by electromagnetic distortions of the different radio frequency hardware components in the device. In recent years, RFF identification is mainly based on Deep learning. As these methods are computational intensive, we have proposed an identification method based on Tangled Program Graph (TPG) [7, 6]. TPG is a new machine learning technique based on genetic evolution which are less complex than DL. Results show that TPGs achieve the same accuracy as a state-of-the-art convolutional neural network with a learning phase duration clearly reduced on CPU. TPGs are also used to analyse both the impact of channel and the receiver radio on the accuracy.

5.7 Sensor aided Energy disaggregation

Participants: Baptiste Vrigneau, Pascal Scalart, Nidhal Balti.

Energy disaggregation, also known as non-intrusive load monitoring (NILM), is the process of analyzing energy consumption in a building and identifying individual appliancelevel energy usage. This approach can provide valuable insights into energy consumption patterns and help reducing overall energy usage, costs, and carbon emissions. This paper [5] proposes a new method for tackling the disaggregation problem by using data from low-cost wireless sensor networks. The proposed approach estimates appliance states using a GMM model and uses these states as features to improve energy disaggregation. The performance of the proposed method was evaluated on a real-world dataset called SmartSense deployed in our lab, and the results showed that it significantly improved the accuracy of conventional NILM disaggregation performance.

5.8 Audio coding

Participants: Pascal Scalart, Thomas Muller.

We recently focused on audio coding schemes based on artificial neural networks. In [12], we propose to analyze and transform the latent space based on an eigenvalue decomposition, in order to modify or even replace the residual vector quantization (RVQ) used in recent codecs such as SoundStream and EnCodec. In particular, the proposed approach brings about 37% of reduction in storage and computational complexity for EnCodec, with no quality degradation.

6 Contracts and Grants with Industry

6.1 CIFRE PhD Grant Prolann/seismowave

Participants: Olivier Berder, Antoine Courtay, Samir-Sharif El Rhaz.

This is a Cifre contract with Prolann/SeismoWave company that includes the supervision of Samir-Sharif El Rhaz.

During the last few years, infrasound sensors have been getting an increased interest, due to their ability to provide a near real-time and continuous monitoring of natural hazards (e.g. climate-related phenomena, detection of seismic event like earthquakes or unusual volcano activity), but also the potential to survey and control comprehensive nuclear Test Ban Treaty over long time periods.

Prolann/SeismoWave is one of the major companies in this field and offers a wide range of infrasound and seismic sensors, some of them based on common patents with CEA. However, energy consumption of current infrasound systems is very high and their deployment and maintenance very heavy.

The goal of this thesis is to propose energy autonomous infrasound devices. To tackle this challenge, power management strategies will be proposed while considering long range communications within the sensor network. The device will be as generic as possible to support different QoS and energy harvesting conditions.

6.2 Eco-counter

Participants: Antoine Courtay, Olivier Berder, Clément Caresmel.

Eco-Counter has been developing various sensors for many years to assess attendance in areas of interest such as natural parks. The compactness of the sensors and their energy autonomy are currently the two major issues in the design of the new family of sensors. To be able to make the sensor itself as discrete as possible, Eco-Counter would in particular like to study the possibility of separating the latter from the counter part (more imposing and consuming in energy).

Since the distance between these two entities can reach several meters, it is necessary to study the various state-of-the-art technologies that are able to communicate reliably and at low energy cost on this scope. Given the strong energy constraints on the sensor side, wired bus technologies will of course be discussed first. The study will then focus on the possibility of communicating by radio between the entities while maintaining correct energy consumption.

6.3 CG-Wireless

Participants: Olivier Berder, Baptiste Vrigneau, Jules Courjault.

CG-Wireless is a consulting company and Design House specialized in designing wireless products. Based in Brittany, CG-WIRELESS is specialized in the design of products using the most advanced radio technologies. CG-WIRELESS carries out in-house research to offer their customers turn- key radio solutions, as platform ready reference design.

The aims of the contract are to study the reinforcement learning for IoT and about SDR solutions for the nodes. A simulation tools for LoRa network optimisation is also developed. It permits to co-found the PhD of Jules Courjault with the European EIT Digital programm.

7 Other Grants and Activities

7.1 National Collaborations

- **ANR JCJC RedInBLack (2023-2026)**
  Participants: Robin Gerzaguet, Olivier Berder, Matthieu Gautier, Paul Bazerque
  TEMPEST attacks target device that unintentionally emits sensible data through an electromagnetic channel. This kind of compromising are due to coupling, hardware impairments or physical proximity between components. Sensitive information emitted by these devices may be recovered passively by any radio component and more particularly by software defined radio, now capable to sample very large bandwidths. The objectives of RedInBlack are many-folds i) Assess new radio fingerprint based methods to identify devices through learning methods fed by large bandwidths features ii) propose coherent and non-coherent decoding methods to recover the sensitive data emitted by the device iii)develop effective methods able to cope with large bandwidths to identify TEMPEST channel and recover sensitive data in real time with the use of a new hardware/software methodology based on Julia langage.

- **ANR Labex CominLabs - NOP (2021-2024)**
  Participants: Matthieu Gautier, Olivier Berder, Robin Gerzaguet, Mickaël Le Gentil
  Intermittent computing is an emerging paradigm for batteryless IoT nodes powered by harvesting ambient energy. It intends to provide transparent support for power losses so that complex computations can be distributed over several power cycles. NOP aims at improving the efficiency and usability of intermittent computing, based on consolidated theoretical foundations and a detailed understanding of energy flows within systems. For this, it brings together specialists in system architecture, energy-harvesting IoT systems, compilation, and real-time computing. NOP consortium is composed of IRISA (Granit team), IETR (SysCom) team, INRIA (PACAP team) and LS2N (SRC team). Within this project, our GRANIT team will develop both hardware and software parts of the platform.

- **ANR PRC - U-Wake (2021-2024)**
  Participants: Matthieu Gautier, Olivier Berder, Mickaël Le Gentil
  ANR U-Wake project aims to achieve a breakthrough in the field of IoT by developing a disruptive wake-up receiver solution based on (1) a bioinspired architecture achieved with an industrial CMOS technology (with transistors operating in deep sub-threshold regime) and (2) Electro Magnetic energy harvesting. The originality lies in the association

of a Radio Frequency (RF) demodulator to a neuro-inspired detector and dataprocessing through a spiking neural network (SNN), resulting in a complete ultra-low power wake-up radio supplied with a voltage of a few 100 mV. The U-Wake consortium is composed of very complementary laboratories in computer science and electrical engineering domains, namely IRISA, IEMN (Lille) and CITI (Lyon). Within this project, our GRANIT team will be in charge of the implementation of the prototype design. In collaboration with IEMN, it will embed the bioinspired IC in a new type of wake-up receiver and with CITI the energy harvester.

- **AMI ADEME Goodfloow (2021-2024)**
  Participants: Olivier Berder, Matthieu Gautier, Mickaël Le Gentil, Clement Caresmel
  GoodFloow offers a solution that automates the monitoring and management of reusable industrial packaging (tertiary packaging), consisting of an IoT to put in each packaging and a web and mobile application. The lack of genericity/reliability of current geolocation systems makes impossible to automate inventories, since it can not be proved who is responsible for industrial packaging in real time.

  GoodFloow therefore wants to design an on-board system making it possible to provide concrete proof of the site responsible for each packaging 24 hours a day, 7 days a week, without human intervention, without infrastructure, and with IoTs having a lifespan equal to those of the packaging (7 to 10 years). To achieve this, the GoodFloow project aims to integrate the following technologies on a suitable electronic card: on-board AI fed by an accelerometer to wake-up the node on particular events, a wake-up radio to discover the neighborhood while consuming quasi nothing, and a multi-radio MAC layer to connect surrounding radio networks and definitely attest the positioning (and eventually the responsible) of the packaging.

  Goodfloow leverages a well-balanced consortium composed of an SME (Goodfloow) and 4 laboratories (Lab-STICC, INRIA Lille, IEMN and IRISA).

- **Images & Réseaux Competitivity Cluster - HIJ (2020-2023)**
  Participants: Olivier Berder, Matthieu Gautier, Clement Caresmel, Mickaël Le Gentil
  The project consists in developing a tracker connected to a LoRa network, leveraging a configurable embedded OS (Operating System) and an energy harvesting system. The main axis of innovation of this tracker are the design of a very constrained energy manager and the use of an OS to create and compile the embedded code using a web interface simplified ('safe & secure by design'), in order to accelerate the integration of the following firmware functionalities: improved quality of service of the LoRa network, secure data transmission, optimized accuracy of geolocation. The leader of HIJ project is ERCOGENER, and the consortium is completed by the SME TICATAG.

7.2 International Collaborations

- **France-Japan ANR/JST Call on EDGE IA : Light-Swift Project (2023-2027)**
  Participants: Olivier Berder, Robin Gerzaguet, Pascal Scalart
  Artificial intelligence (AI) brings without any doubt huge opportunities to optimize effi-

ciency of every industrial application and is a key point of Industry 4.0. The deployment of various sensors in factories, also called Industrial Internet of Things (IIoT) can either help workers in charge of machine maintenance by detecting abnormal behaviours, thus preventing machine breakdown, or help to localize objects or persons in such complex environments. AI algorithms probably represent the best solution to cope with the huge amount of data provided by sensors, but their complexity is also a severe drawback and the processing is mainly centralized.

Energy is crucial for IIoT, since the more sensors are deployed, the more difficult it becomes to ensure sufficient energy, as batteries would need to be recharged more frequently. Moving the processing closest as possible to the sensors would avoid energy hungry transmissions of data. Most of the latter is indeed useless, since AI algorithms need to be fed with descriptors more than raw data. To further enhance energy efficiency of Edge AI, LIGHT-SWIFT aims at proposing a new methodology to reduce the complexity of AI algorithms, paving the way for sustainable smart sensors in Industry 4.0. This methodology will be applied to sound sensor nodes able to detect unusual situations, either in machine behaviour but also in the general context of the factory. In case of emergency, the system may have to cope with massive amounts of additional data, entailing a crucial need for extremely reliable high data rate transmissions, despite the limited spectrum resources. The methodology of LIGHT-SWIFT project will therefore be applied to the wireless transmissions themselves, to optimize the radio resource access, while achieving the best possible energy efficiency. To reach this goal, our project will leverage a well-balanced consortium composed of two academic partners, IRISA and NII, that work respectively on energy efficient wireless sensor networks and edge AI for wireless communications, the Small and Medium-sized Enterprise (SME) Wavely specialized in sound event detection for IIoT, and one of the largest telecommunications operating companies in the world, NTT, with applications in Industry 4.0.

8 Dissemination

8.1 Scientific Responsibilities

- O. Berder, M Gautier and B. Vrigneau are members of Scientific Committee of IUT Lannion.
- R. Gerzaguet is member of the Scientific Committee of ENSSAT.
- R. Gerzaguet is a member of the IRISA Laboratory Council.
- R. Gerzaguet is a member of Collége numérique France 2030
- O. Berder is a member of the Scientific Committee of EUR Digisport.
- O. Berder is a member of Labelling Committee (CSV) of Images & Networks cluster
- O. Berder is a coordinator of Wireless Devices topic at CNRS GDR SoC2.
- M. Gautier is a coordinator of Architecture and algorithms Topic at GDR ISIS.

8.2 Involvement in the Scientific Community

PhD committees:

- O. Berder served as the president of Defence Committee for the PhD of Ruochen Ding, *Contribution à la conception et à la modélisation de wake-up radio pour réseaux de capteurs*, defended at Université CÃ´te d'Azur, October 19 2023
- M. Gautier served as an reviewer for the PhD of Camille Monière, *Real-Time Implementation of a Quasi-Cyclic Short Packet (QCSP) Receiver*, defended at Université de Bretagne Sud, January 4 2023

Editorial and reviewing activities:

- O. Berder is a member of the Editorial Board of *International Journal of Distributed Sensor Networks*
- O. Berder is a member of the Editorial Board of *Wireless Communications and Mobile Computing*
- O. Berder is a member of the Editorial Board of *Sensors*
- O. Berder is a member of Technical Program Committee of IEEE PIMRC, IEEE SAS, ACM EWSN, ICT and is a reviewer for IEEE TSP, TWC, ToN, JSAC, ICC, GLOBECOM
- M. Gautier was a member of technical program committee of IEEE WCNC, IEEE PIMRC and IEEE Globecom.
- B. Vrigneau was a member of technical program committee of IEEE PIMRC and 4th International Workshop on Non-Intrusive Load Monitoring.
- A. Courtay served as a reviewer for GRETSI.
- M. Gautier served as a reviewer for GRETSI and Internet Technology Letters.
- B. Vrigneau served as a reviewer for IEEE Communications Letters, PIMRC, ISTC, WCMC, MDPI Sensors, IEEE Trans. on Vehicular Technology, Gretsi.
- Robin Gerzaguet served as a reviewer for GRETSI, IEEE EUCNC, IEEE WCNC, IEEE Access, IEEE Transaction on Wireless Communications and IEEE Transactions on Aerospace and Electronic Systems.

8.3 Teaching Responsibilities

IUT stands for *Institut Universitaire de Technologie* and ENSSAT stands for *École Nationale Supérieure des Sciences Appliquées et de Technologie* and is an *école d'Ingénieurs*. Both are located in Lannion and part of the University of Rennes.

- O. Berder is Deputy Director of IUT Lannion.

- A. Courtay is supervising the first year students of the Electronics Engineering department of ENSSAT.
- R. Gerzaguet is supervising the third year students of the Electronics Engineering department of ENSSAT.
- R. Rocher is the Head of the Network and Telecommunications Department at IUT Lannion.
- M. Gautier is member of the French National University Council since 2015 in signal processing and electronics (Conseil National des Universités en 61e section) - elected again in 2019.
- M. Gautier is supervising the second year students of the Network and Telecommunications Department at IUT Lannion and is in charge of Studies Pursuit.
- O. Berder is in charge of Studies Pursuit of Physical Measurements Department at IUT Lannion.
- B. Vrigneau is the Head of the new department Multimedia and Internet at IUT Lannion.

8.4 Teaching

Teaching highlights:

- An educational publication associated with the teaching activities on IoT and embedded systems has been published to french j3eA journal [1].
- A new lecture dedicated to hardware security has been created and is based on the work on RF security carried by Granit Team. The lab sessions will involve practical experiments, data collection, analysis, and algorithm design related to real-time screen eavesdropping using SDR.

Main courses:

- O. Berder: signal processing, 70h, IUT Lannion (L2)
- O. Berder: sensors and control, 90h, IUT Lannion (L2) and 25h, UFAZ Bakou, Azerbaidjan (L2)
- O. Berder: digital systems, 80h, IUT Lannion (L1)
- O. Berder: Energy Harvesting, 40h, IUT Lannion (L3)
- O. Berder: IoT and connected objects, 14h, ENSSAT (M2)
- C. Caresmel: general electronics, 12h, ENSSAT (L3)
- C. Caresmel: system engineering, 12h, ENSSAT (L3)

- A. Courtay: digital electronics, 116h, ENSSAT (L3)
- A. Courtay: PCB conception, 14h, ENSSAT (L3)
- A. Courtay: PCB conception, 20h, ENSSAT (M1)
- A. Courtay: PCB conception, 16h, IUT Lannion (L3)
- A. Courtay: digital electronics communication interfaces, 68h, ENSSAT (M1)
- A. Courtay: digital electronics: Laser diode driver, 40h, ENSSAT (M1)
- M. Gautier: computer architecture, 36h, IUT Lannion (L1)
- M. Gautier: telecommunications, 138h, IUT Lannion (L1)
- M. Gautier: digital communications, 30h, IUT Lannion (L2)
- M. Gautier: Embedded systems and connected objects, 90h, IUT Lannion (L3)
- M. Gautier: IoT and connected objects, 10h, ENSSAT (M2)
- R. Rocher: electronics, 44h, IUT Lannion (L1)
- R. Rocher: telecommunications, 82h, IUT Lannion (L1)
- R. Rocher: signal processing, 12h, IUT Lannion (L2)
- R. Rocher: digital communications, 48h, IUT Lannion (L2)
- P. Scalart: non-linear optimisation, 18h, Master by Research (SISEA) and ENSSAT (M2)
- P. Scalart: parametric modelization, optimal and adaptive filters, 24h, Master by Research (SISEA) and ENSSAT (M2)
- P. Scalart: source coding, 14h, Master by Research (SISEA) and ENSSAT (M2)
- P. Scalart: cellular networks, 24h, ENSSAT (M2)
- P. Scalart: digital communication systems, 32h, ENSSAT (M1)
- P. Scalart: random signals and systems, 12h, ENSSAT (M1)
- R. Gerzaguet: Micro-electronics, 46h, ENSSAT (L3)
- R. Gerzaguet: Digital Signal processing, 60h, ENSSAT (M1)
- R. Gerzaguet: Wireless network, 9h, ENSSAT (M1)
- R. Gerzaguet: Wireless communication, 16h, ENSSAT (M2)
- R. Gerzaguet: GIT & Test Driven Development, 8h, ENSSAT (L3)

- R. Gerzaguet: System On Chips, 22h, ENSSAT (M2)
- R. Gerzaguet: Hardware security, 18h, ENSSAT (M2)
- B. Vrigneau: computer architecture, 14h, IUT Lannion (L1)
- B. Vrigneau: telecommunication, 20h, IUT Lannion (L1)
- B. Vrigneau: maths, 24h, IUT Lannion (L2)
- B. Vrigneau: sciences, 190h, IUT Lannion (L1, L2, L3)
- B. Vrigneau: Data acquisition part 1, 25h, UFAZ Bakou, Azerbaidjan (L3)

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