Activity Report 2017

Team GRANIT

Adaptive Algorithms and Architectures for Energy-efficient Wireless Systems

D3 – Architecture

1 Team

Name	Forename	Position
Berder	Olivier	Full Professor, UR1 (IUT Lannion)
Carer	Arnaud	Research Engineer^{+}, UR1
Carquin	Émilie	Research Assistant, UR1 (ENSSAT Lannion)
Courtay	Antoine	Associate Professor, UR1 (ENSSAT Lannion)
Demigny	Didier	Full Professor*, UR1 (IUT Lannion)
Gautier	Matthieu	Associate Professor, UR1 (IUT Lannion)
Gerzaguet	Robin	Associate Professor^{o}, 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)

$^{+}$ Shared with CAIRN team
* Associate member
^{o} Since 09/2017

Table 1: GRANIT permanent members

The GRANIT team comprizes 8 permanent members: 2 full professors (*Professeur des Universités*), 5 associate professors (*Maître de conférences*) and one research engineer (shared with CAIRN Team[1]). There are currently 4 full time PhD students in the GRANIT team, while 3 others are co-supervised with the CAIRN team. Table 1 lists the permanent staff and table 2 the current PhD students and other staff.

Didier Demigny is considered as an associate member of GRANIT since he still has a research activity with some of GRANIT members, but its administrative and teaching tasks are very time consuming. Didier Demigny was director of the Institute of Technology of Lannion and is now vice-president of University of Rennes 1.

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

[1]GRANIT is the result of the split of the CAIRN team (which is still another team of IRISA) into two different parts, and all of the GRANIT members were formerly belonging to CAIRN. This decision was motivated by two main reasons: CAIRN had reached a critical size (more than sixty members) and the scope of its research was really broad. Some research is still common and engineers are supporting developments of both teams.

Name	Forename	Status	Period
Ait Aoudia	Fayçal	PhD	10/2014 - 09/2017
Gleonec	Philip Dylan	PhD	Since 10/2015
Kazdoghli Lagha	Marwa	PhD	Since 10/2017
Le	Xuan-Chien	PhD+	10/2013 - 04/2017
Nguyen	Van Thiep	PhD	10/2013 - 09/2017
Roux	Baptiste	PhD+	10/2014 - 11/2017
Roux	Nicolas	PhD+	Since 10/2016
Tran	Mai Thanh	PhD+	Since 10/2013
Le	Xuan-Chien	Post-doc	Since 05/2017
Abdmouleh	Ahmed	ATER	09/2016 - 08/2017
Le Gentil	Mickaël	Research Engineer	Since 09/2016

+ Shared with CAIRN team

Table 2: GRANIT other staff

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.

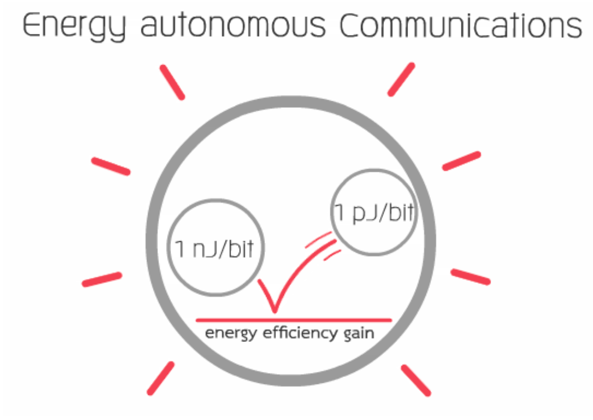

Figure 1: Transmission Energy efficiency target for the next decade

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 (4G, 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[2]. Thus, our proposal relies on high-level synthesis (HLS) in order to bridge the gap between high-level specifica-

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

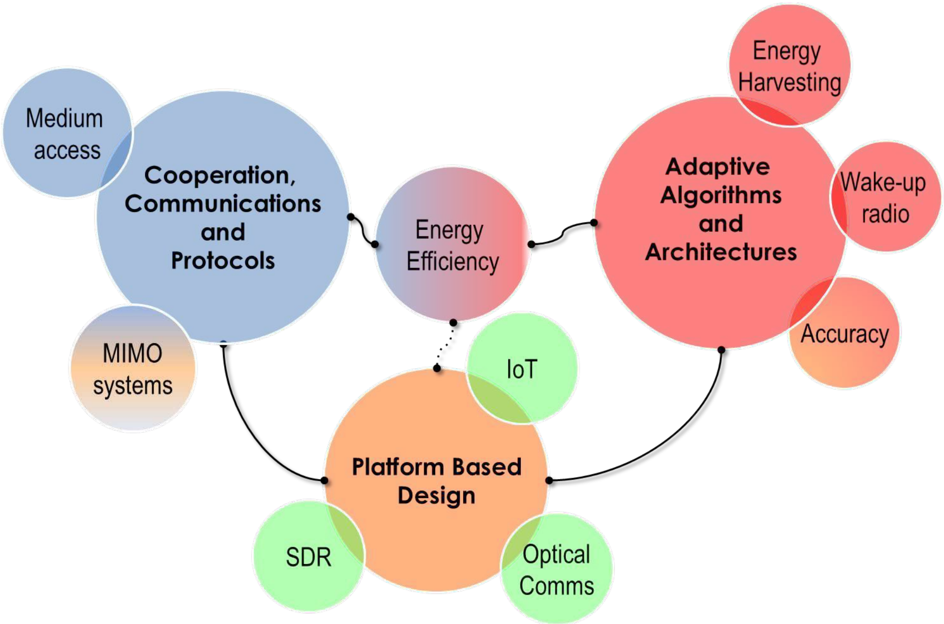

Figure 2: GRANIT Research Topics

tions and hardware implementation[3]. Depending on the hardware target, hardware/software partitioning, reconfiguration capability or power management will be included in the design flow.

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 CAIRN 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 platforms (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 Adaptive algorithms and architectures

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.

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

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.

Energy harvesting and Power Management 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)[4].

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.

[4] 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

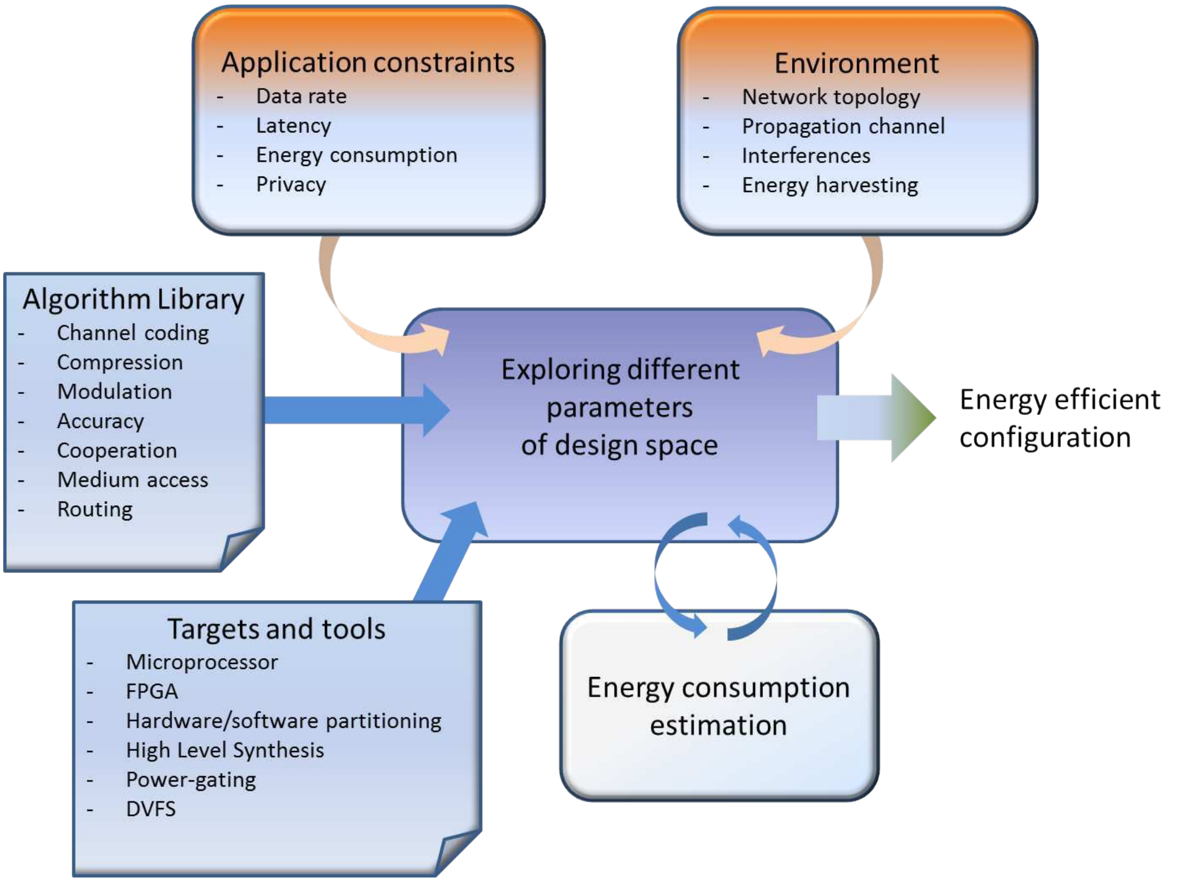

Figure 3: GRANIT Optimization Methodology

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 [5] 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 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,

[5] 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

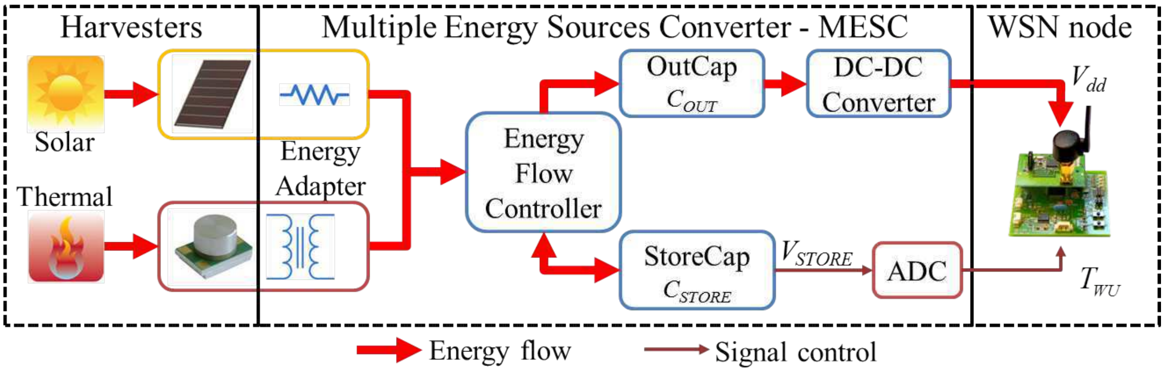

Figure 4: GRANIT Hardware Architecture of our Energy Harvesting Nodes

- 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.

Fixed point arithmetic Fixed-point architectures manipulate data with relatively small word-lengths, which could offer the advantages of a significantly lower area, latency, and power consumption in embedded systems. However, fixed-point arithmetic introduces quantization noises which modify computation accuracy and, so, the application integrity. Our approach consists in studying fixed-point accuracy privileging analytical methods. These ones reduce drastically the conversion time compared to methods based on simulation during the floating-point arithmetic to fixed-point arithmetic conversion process of the application.

Our studies include :

- Efficient implementation of equalization and synchronous algorithms for digital applications
- Adaptive precision scaling: modifying precision according to channel and environment modifications
- Multi-constraints implementations of digital communication applications: the idea is to find a satisfying implementation according to different constraints (multi accuracy, and/or latency, and/or cost)
- Sampling frequency effects on computing accuracy
- Study of new arithmetics for digital applications (approximate computing, vectorial quantization. . .)

3.3 Cooperative Communications and Protocols

In most of wireless sensor networks, the radio in both transmit and receive modes consumes the bulk of the total power consumption of the system. The diversity achieved by cooperative communications represent a very promising opportunity to decrease the transmit power. To illustrate this statement, let us consider a Wireless Body Area Network (WBAN), where the channel conditions are very different if we consider an on-body transmission or a transmission towards a distant base station. Within the WBAN, signals will experience strong shadowing effects due to body motion and the propagation loss is no more directly proportional to the distance between the transmitter and the receiver. In this context, the instantaneous position of the nodes can have a great impact on the link reliability and cooperative relaying schemes and opportunistic protocols are very useful to keep the same QoS without increasing the transmission power. On the other hand transmissions from the WBAN to base stations can be considered as less time-varying. Considering the possibility for nodes on-body to know the channel state information, distributed MIMO precoders can be designed in order to decrease the energy required for this kind of transmissions.

Another domain of application is the cooperation in order to take a local decision about the data to be sent. Unlike a centralized architecture where all data are loaded in a server leading to a significant transmission consumption, a local cooperation will take the advantage of sensor diversity and will send only the pertinent data in order to save energy with the best radio-computation trade-off, and eventually harvesting. It is also a solution to respect the privacy.

In spite of this ability of cooperative schemes to increase the energy efficiency of WSN, there is still very few practical experiments since they need both hardware and software improvements. The existing MAC layer protocols are not well suited to cooperative schemes and cooperative MAC protocols have to be designed. Cross-layer optimizations will then be investigated in our team to reach the maximum energy efficiency.

Cooperative MIMO and relay techniques The transmission mode classically used in wireless sensor networks to transmit a message from a source to a destination separated by a fairly large distance is multi-hops or multi-stages. However, some cooperative techniques allow an increase in the radio range of devices or a reduction in energy spent to reach the same distance.

- Relay techniques: Amplify-and-Forward (AF) and Decode-and-Forward (DF)
- Cooperative MIMO strategies (Fig 5)
- Opportunistic routing

The GRANIT team addresses these different possibilities taking especially into account the energy criterion, the most important constraint in wireless sensor networks. Besides performance evaluation through analytical derivations, the cooperative strategies are also simulated through network simulators. This implies the design of dedicated MAC protocols, but makes us able to estimate with accuracy the real gain of cooperation. Among the metrics we use, the energy-delay trade-off is very interesting for wireless sensor networks.

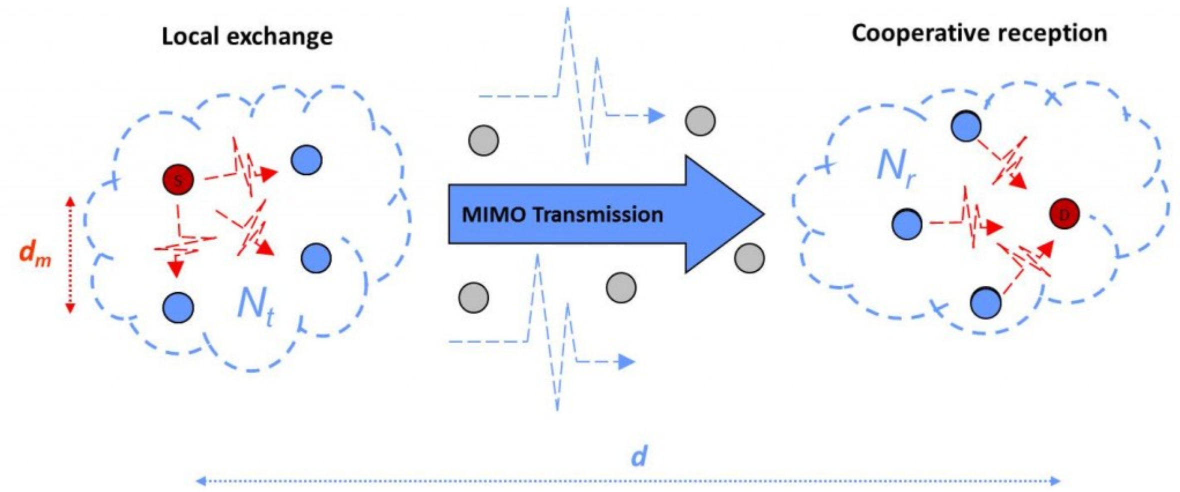

Figure 5: Cooperative MIMO transmission. Phase 1: the source exchanges information with its neighbors. Phase 2: synchronous MIMO transmission towards the destination group. Phase 3: the receiver sends the received signals towards the destination which combines the signals received.

Cooperative and opportunistic protocols Although there is obviously an enormous interest in cooperative techniques in the research community, most of the performance analysis for cooperative communication is widely studied at physical layer. In order to make cooperative techniques be able to be utilized in the next generation of wireless networks, the higher layer protocols such as medium access control (MAC) layer or routing layer, must be thoroughly considered. Among the higher layers, MAC layer is responsible for regulating the shared wireless medium access of the networks, therefore, it has great influences on the network performance. In addition, MAC layer is also expected to improve throughput or energy efficiency, reduce delay while keeping the collisions to a minimum.

On the other hand, opportunistic routing aims at exploiting sporadic radio links to improve the connectivity of multi-hop networks and to foster data transmissions. However, the benefit of opportunistic relaying may be counteracted due to energy increase resulted from multiple active receivers. Therefore, we are conducting thorough analysis of opportunistic relaying efficiency under the different realistic radio channel conditions, to find the optimal tradeoff between two objectives: energy and latency minimizations, with a hard reliability constraint.

MIMO precoding In the last decades, MIMO systems were exploited to offer spatial diversity and precoders were designed for a closed-loop solution with the channel state information at the transmitter through a feedback link. Some well-known solutions optimize the capacity, the mean square error, the signal to noise ratio or the minimum distance. Nowadays, it exists a lot of different precoders with pros and cons and, according to the environment and quality of service, the challenge is to choose the most energy-efficient solution. The main concerns of our research are the performance evaluation and the decrease of the complexity thanks to approaches based on the minimum distance (dmin) and its probability density function (pdf).

Hereafter are some of the research paths we are following :

- Obtain the pdf of dmin for any precoder : modulation size, number of substreams, even a cooperative scheme with synchronization error
- Consider several channel statistics (Rayleigh, Rice, correlation), ie BAN, indoor, or outdoor context
- Propose new quantization methods of the feedback link in order to adapt the method from the open-loop to the full CSI and associated architecture solutions for precoders
- Propose new estimates of the bit error rate and extend it to channel coding with soft or iterative decision

Precoding techniques can also be used in a cooperative manner for wireless sensor networks. As stated here above, when propagation channels are varying slowly enough, it makes it even possible to distribute the precoding among cooperative nodes to dynamically adapt the signal transmission to the propagation channels and avoid deep fading.

4 Application Domains

4.1 Next generation of mobile communications

The next generation of wireless communications, namely 5G, will address a new kind of user: in addition to connect people, the next breakthrough is the connectivity of machines with other machines, referred to as 'M2M', which is the basis of the IoT paradigm[6]. Thus, in addition to a massive increase in the number of accesses (i.e. throughput increase) and current spectrum crisis issues, new requirements must be taken into account. A claimed advantage of M2M is remote steering and control of real and virtual objects. Hence, the required latency of such communications must be low enough to enable a round-trip delay from devices through the network back to devices of approximately 1ms. Another requirement we want to highlight is the flexibility the connected objects must have to respond to the number of standard modes. Indeed, in order to meet the time and space fluctuations of a service (i.e. throughput), in order to make several classes of objects connect together and in order to answer the spectrum scarcity issue, it is claimed that the new generation of wireless communications must be able to change their features in real time. Finally, reducing energy consumption is an on-going major challenge for two reasons: the first is the total energy consumption of ICT (Information and Communications Technologies) infrastructure that must be reduced; the second is the life cycle of new types of devices (e.g. Wireless Sensor Network node, IoT device) that must significantly increase to be massively deployed and used.

[6] G. Fettweis, The Tactile Internet - Applications & Challenges, *IEEE Vehicular Technology Magazine*, March 2014

4.2 Wireless Sensor Networks

Wireless Sensor Network (WSN) technologies are also fast becoming a major part of our life with applications ranging from mobile health, smart homes, energy efficient buildings, environmental/context monitoring, assisted living, etc. The progress in this area is fast paced with power consumption reduction being one of the main challenges. One of the major promising advances is in the area of smart sensors where the computation is close to the sensor and only information or a command is being transmitted. This concept promises drastic savings of power, improvements in security, but also brings new challenges in areas such as ultra low power acquisition platforms, novel signal processing, and ultra low power reliable communications. Wireless Body Area Networks (WBAN) are a subclass of WSN, where the sensors are close to the body. This characteristic brings some of the biggest constraints in designing these networks in terms of power, size, security, reliability, etc. Despite these constraints, WBAN are listed as one of the most promising applications of WSN with many potential applications in health, rehabilitation, sports, and entertainment.

5 Hardware and Software

5.1 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. 6. 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.

5.2 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 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.

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

Figure 6: PowWow WSN Platform with Energy Harvesting

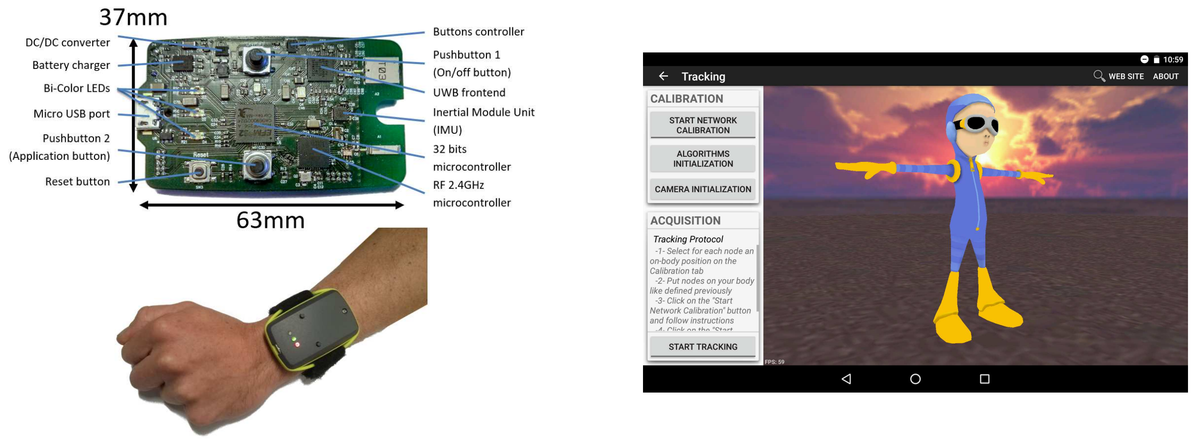

Figure 7: Zyggie motherboard and avatar application

sports movements, robotics, non-verbal communication in fighting situations. A new version of this platform is being designed, that will incorporate au Ultra Wide Band (UWB) radio for more precise positioning of the sensors.

5.3 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 architectures 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 I**o**T heterogeneou**s** **e**mbedded sys-

tems) will be deployed in 2017-2018. The platform will be based on USRP-310 from Ettus that are based on Zynq platform. It will allow to developp efficient High Level Synthesis methods and propose rapid prototyping tools in the IoT context. The SDR platform is partially funded by the Brittany region (CD22).

5.4 Real-time FPGA processing for optical access networks

Designed during the ANR FAON project, this platform is a prototype for 1Gbit/s QAM receiver for the optical access networks with Frequency Division Multiplexing (FDM). This prototype is based on a Virtex 7 FPGA and four analog to digital convertors sampling at 1 Gsps. This real-time prototype validates our algorithms for equalization and synchronization, but also a new FPGA design flow based on HLS (High Level Synthesis) and finally, the feasibility of frequency multiplexing for access networks. The prototype has been realized in collaboration with UMR CNRS FOTON for the RF front-end and Orange Labs for the integration in the system and the tests. The GRANIT team has designed the algorithms for demodulation as well as the FPGA implementation.

5.5 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, 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.

6 New Results

6.1 Software Defined Radio

Participants: Robin Gerzaguet, Matthieu Gautier, Mai Thanh Tran.

5G will have to cope with a high degree of heterogeneity in terms of services and requirements. Among these latter, flexible and efficient use of all available non-contiguous spectra for different network deployment scenarios is one challenge for the future 5G. To maximize spectrum efficiency, the 5G air interface technology will also need to be flexible and capable of mapping various services to the best suitable combinations of frequency and radio resources. Such requirements are not satisfied by legacy CP-OFDM and alternative multicarrier waveforms such as UFMC and FBMC partially meet them.

We have introduced in [12] a new quasi-orthogonal waveform called Block-Filtered OFDM (BF-OFDM) that combines most of the advantages of the aforementioned waveforms at the

price of slight complexity increase. The proposed waveform offers the same performance in presence of multipath channel as CP-OFDM and is also flexible and scalable which paves the way for future multi-service scenarios. First experiments in new 3.5GHz band has been done, based on a software defined radio architecture [11].
This work has been granted by the 2017 Best Paper Award in ICC [12].

6.2 Energy Harvesting and Power Manager Design

Participants: Fayçal Ait Aoudia, Olivier Berder, Matthieu Gautier, Philip Dylan Gleonec.

Energy harvesting is a promising approach to enable autonomous long-life wireless sensor networks. As typical energy sources present time-varying behavior, each node embeds an energy manager, which dynamically adapts the power consumption of the node to maximize the quality of service, while preventing power failure.

In [8], RLMan, a novel energy management scheme based on reinforcement learning theory, is proposed. RLMan dynamically adapts its policy to time-varying environment by continuously exploring, while exploiting the current knowledge to improve the quality of service. The proposed energy management scheme has a very low memory footprint, and requires very few computational power, which makes it suitable for online execution on sensor nodes. Moreover, it only necessitates the state of charge of the energy storage device as an input, and therefore is practical to implement. RLMan was compared to three state-of-the-art energy management schemes, using simulations and energy traces from real measurements. Results show that using RLMan can enable almost 70% gains regarding the average throughput.

In the case of multi-hop networks, each node both performs measurements to produce data to be sent to a sink, and relays data packets from other nodes. In [1], we proposed a distributed algorithm for computation of fair packet rates for multi-hop energy harvesting wireless sensor networks. The packet rate computation problem is formulated as a convex optimization problem, and using the fast alternating direction method of multipliers, the original problem is decomposed into smaller sub-problems that can be solved in parallel. Simulations using real indoor light energy traces show that the algorithm computes high accuracy solutions, even with a low median number of iterations (10 or less). By setting the stop criteria parameter, a compromise can be set between the accuracy of the solution and the number of iterations required.

Finally, a demonstration of our fyzzy-logic based ernergy manager has been done in IEEE SiPS conference [17].

6.3 Combining Long range communication and Wake-up radio

Participants: Fayçal Ait Aoudia, Olivier Berder, Matthieu Gautier.

Wireless communication between distributed sensor devices and the host stations can consume significant energy, even more when data needs to reach several kilometers of distance.

In [13], we present an energy-efficient multi-sensing platform that exploits energy harvesting, long-range communication and ultra-low-power short range wake-up radio to achieve self sustainability in a kilometer range network. The proposed platform is designed with power efficiency in mind and exploits the always-on wake-up radio as both receiver and a power management unit to significantly reduce the quiescent current even continuously listening the wireless channel. Moreover the platform allows the building of an heterogeneous long-short range network architecture to reduce the latency and reduce the power consumption in listening phase at only 4.6μW. Experimental results and simulations demonstrate the benefits of the proposed platform and heterogeneous network.

The latter platform has been used in [3] to achieve both energy efficient and low latency communication in heterogeneous long-short range networks. A hardware architecture as well as a protocol is proposed to exploit the benefits of these two communication schemes. Experimental measurements and analytical comparisons show that the proposed approach remove the need for a trade-off between power consumption and latency. This paper has also been presented during the GDR Soc-Sip conference [16].

6.4 Modeling MAC Protocols in WSNs (including Wake-up radio)

Participants: Fayçal Ait Aoudia, Olivier Berder, Matthieu Gautier.

When studying MAC protocols, analytic models are required to understand the fundamental limits of the different schemes, to investigate their performance and to optimize their parameters. In [2], we propose a generic framework for modeling MAC protocols, which focuses on energy consumption, latency and reliability. The framework is based on absorbing Markov chains, and can be used to compare different schemes and evaluate new approaches. Experimental measurements on real hardware were performed to set framework parameters with accurate energy consumption and latency values, to validate the framework, and to support our results [9].

6.5 Indoor Localization

Participants: Olivier Berder, Arnaud Carer, Antoine Courtay, Sébastien Fontaine, Mickaël Le Gentil, Pascal Scalart.

Indoor localization with UWB can be a noisy context due to fading and/or multipath. A solution is to increase number of anchors and use an algorithm based on simple trilaterations to get a good compromise between number of computations and accuracy. In [10], we proposed a localization algorithm named Best Anchor Selection for Trilateration (BAST) that outperforms low complexity state of the art algorithms. The anchor selection relies on position prediction and takes into account noise estimation. A wearable, light and low power Wireless Sensor Network (WSN) prototype (named *Zyggie*) including an UWB chipset has been developed for algorithms comparison. Experimental testbed using real cases experiments show that BAST can give from 1.26 up to 4.17 times better precision when the mobile/person is in movement (e.g. tennis player).

6.6 Non Intrusive Load Monitoring

Participants: Nicolas Roux, Xuan-Chien Le, Baptiste Vrigneau.

Knowing the plug-level power consumption of each appliance in a building can lead to drastic savings in energy consumption. Non-Intrusive Load Monitoring (NILM) is a method for disaggregating power loads in a building to the single appliance level, without using direct sensors or electric meters. While the thesis of Xuan-Chien aimed at improving performance of Non-Intrusive Load Monitoring with low-cost sensor networks, the work of Nicolas Roux is to address the issues of NILM inaccuracy in the context of commercial and industrial buildings, by adding to the problem data from a low-cost, non-dedicated, smart sensor network. The considered problem is the power estimation of each device state, given partial knowledge. Formulated using linear algebra, the problem is solved to estimate the power load values of these steady states on sliding windows of data with varying size.

6.7 Cooperative Communications

Participants: Olivier Berder, Baptiste Vrigneau, Pascal Scalart.

Taking into account not only the transmission power at each transmission node but also the processing power consumed in each reception node on the overall end-to-end performance, we formulated in [4] the optimization problem aiming to minimize the total power consumption. This optimization is performed under a target performance constraint, and the total power consumption stands for the sum of the transmission power and the processing power consumed in the decoding (neglecting other forms of power consumption). Our analysis relies on the characterization of an information-theoretic bound on the decoding power of any modern code to achieve a specified bit error probability while operating at a certain gap from the capacity. As this bound is built on the sphere-packing analysis, the present study focuses on message-passing decoders. Using this theoretical framework, the improvement of well-known cooperative protocols over the original non-cooperative point-to-point system system is reinvestigated in terms of total power consumption. Thanks to this theoretical framework, a new classification of the studied cooperative protocols is given revealing some surprizing conclusions. In particular, the selective decode-and-forward protocol is no more constantly preferred to its simpler alternative, i.e. the decode-and-forward protocol.

6.8 MIMO Precoding

Participants: Olivier Berder, Baptiste Vrigneau.

In [5], we proposed an imperfect-quantized-feedback-based beamforming scheme for a generalized multiple-input single-output (MISO) free space optical (FSO) system over Gamma-Gamma fading channels with pointing error. A signal-to-noise ratio (SNR) adaptive error tolerant weighting (ETW) scheme is introduced and is optimized according to the SNR of the feedback link. In comparison to the considered arbitrarily fixed SNR-based ETW scheme, the proposed SNR adaptive ETW scheme provides significant performance gain (coding gain) almost equivalent to error free optimal weighting scheme (EFOWS). Closed-form expressions for the upper bound of the asymptotic average bit-error rate (BER) and the ergodic capacity of the proposed schemes are obtained with the help of order statistics. By minimizing the derived average BER, optimized transmit weights for the transmit apertures are achieved under erroneous feedback over Gamma-Gamma fading with pointing errors. Numerical results show that the proposed new error tolerant scheme outperforms the well-known repetition coding (referred to as the uniformly weighted scheme).

The same approach is used in [6] to propose an imperfect quantized feedback-based diagonal precoding scheme for generalized orthogonal space-time block codes in an $N \times 1$ multiple-input single-output (MISO) wireless communication system employing M-QAM constellation. At first, a tight approximate closed-form expression of average symbol-error-rate (SER) and an exact analytical expression of outage probability are derived under imperfect feedback information with the help of order statistics. By minimizing the derived average SER, optimized transmit weights for the diagonal precoding matrix (based on feedback bits) are obtained. Later, a closed-form expression of the ergodic capacity with erroneous feedback bits for arbitrary MISO system is also provided by using the moment generating function approach. Further, numerical results show that the considered error-tolerant schemes outperform the uniform power allocation scheme in term of all the investigated performance metrics.

Besides classical criteria such as capacity or bit error rate, the diversity-multiplexing trade-off (DMT) is now widely used to evaluate the performance of designed precoders. We proposed in [15] a method to obtain DMT of multi-form MIMO precoders. Although several multi-form solutions were found, to obtain their theoretical performance is still difficult. In order to tackle this challenge, we propose to investigate the minimal distance approach: starting from the probability density function of a square minimum distance, we obtain the outage probability and diversity-multiplexing trade-off (DMT) at operational SNR. We arbitrarily choose the max-d min precoder based on the maximization of a minimal distance using the CSI at the transmitter (closed-loop). This expression is validated by simulations and comparisons between different MIMO precoding schemes are performed. The method can be applied to others precoders and fading channels.

6.9 Optical Communications

Participants: Arnaud Carer, Robin Gerzaguet, Pascal Scalart.

M-ary quadrature amplitude modulation (M-QAM) in combination with coherent detection and digital signal processing (DSP) becomes now a promising candidate for next generation optical transmission systems. This is made possible notably thanks to technical progress in photonic integrated circuits (PICs) allowing the fabrication of monolithically integrated optical circuits for M-QAM optical signal generation. Despite the amazing performance of these circuits, there are still some issues, in particular concerning the nonlinear gain of electrical amplifiers, the control of phase shifts in optical waveguides and cable lengths or circuit paths on printed boards. For all these reasons the resulting signal may present gain and/or phase imbalance, globally referred to as IQ imbalance.

We investigated in [7] and [14] transmitter (Tx) IQ imbalance compensation based on the blind adaptive source separation (BASS) method in a dual polarization M-QAM optical coherent system. The robustness of the BASS method against the residual carrier frequency offset (CFO) is numerically investigated and compared to that of the Gram-Schmidt orthogonalization procedure (GSOP). We further validate experimentally the proposed method with

10-Gbaud optical 4-QAM and 16-QAM signals at 30° and 10° phase imbalance, respectively, with simulated impairments. More specifically, in the presence of 5×10^{-6} residual CFO (normalized to the sample rate), the optical signal-to-noise ratio (OSNR) penalty reduction of the BASS method compared to the GSOP method is 1 dB for 4-QAM at a bit-errorratio (BER) of 2×10^{-3} and 2 dB for 16-QAM at a BER of 10^{-3}. In contrast to the GSOP that requires an independent block, the BASS method can be integrated into an equalizer, simplifying the operation and allowing parallel implementation.

For Celtic+ Sendate European project, a new fast tunable laser control board was designed, allowing tunable speed and grid definition. This new controller can be used to enhance performance of software defined networks with elastic interface.

7 Contracts and Grants with Industry

7.1 CIFRE PhD Grant Wi6Labs

Participants: Olivier Berder, Matthieu Gautier, Philip Dylan Gleonec.

This is a Cifre contract with Wi6labs compagny that includes the supervision of Philip Dylan Gleonec. The goal of this thesis is the design and the implementation of power management strategies for long range radio modules equipped energy harvesting.

7.2 Ericsson: Connected tennis court

Participants: Olivier Berder, Arnaud Carer, Antoine Courtay, Mickaël Le Gentil.

A parternship was formed with Ericsson and M2S laboratory around Tennis activities. Sportman effort measurement become an interesting information for several applications like training or getting live statistics during matches. These works concern the use of the Zyggie prototype and a video system developed by Ericsson. We combined motion information, sportman geolocation and ball trajectory to determine what type of stroke was done (forehand, backhand, etc), quality of the stroke, player movements and ball movement on the court. To this aim, we used motion sensing with inertial modules, UWB distance measuring and low cost video tracking with Raspberry Pi.

7.3 AMG Microwave

Participants: Arnaud Carer.

Due to obsolete components, AMG Microwave company needed to update an old system of marine signaling. AMG microwave wanted to take advantage of this update to improve the digital part of the system. The company used the skills of Granit team to carry out Captronic expertise. Granit has proposed a new digital architecture to improve performance, to facilitate maintenance, to increase battery life and to reduce system costs.

7.4 Eco-counter

Participants: Arnaud Carer, Mickaël Le Gentil, Pascal Scalart.

The company Eco-counter needed to update its bike counting system to maintain the competitiveness of its product with increased competition. Granit team suggested the use of a component initially designed to produce contactless buttons. A service is on-going with the company to validate this new technological solution and to propose algorithmic improvements.

7.5 Feichter electronic

Participants: Arnaud Carer, Pascal Scalart.

This work aimed at designing a radio system for high-quality audio streams, since none of the existing systems on the market was meeting the requirements of the society. This collaboration resulted in a co-supervised internship to evaluate the possible technologies. Because of the satisfactory results of the internship, the collaboration is still on-going.

8 Other Grants and Activities

8.1 International Collaborations

- **EU CELTIC+ SENDATE TANDEM (2016-2019)**

  Participants: Olivier Berder, Arnaud Carer, Pascal Scalart

  TANDEM is sub-project from the CELTIC+ SENDATE project. TANDEM addresses the challenge for a new network infrastructure with reference to high volatile data traffic of mobile linked up objects. A dynamic switching and a reliable transport of huge amounts of data as well as a handover of sensible, time critical application data without any interruptions must be provided between data centers.

  Within the metro area, essential elements are virtualized: integrated nodes consisting of traditional DCs (RAM, processor) but also e.g. virtualized DSL- and radio access (vRAN) network elements or IP-router and optical network elements like cross-connects. Virtualization shall lead to a flexible arrangement of single modules and to a dynamic provision of resources according to application demands. Here latency and bandwidth but also QoS classes and findings from simulative traffic investigations will be considered.

  Furthermore a common SDN-based control-plane will be developed for an optimized control of network elements across levels. The first underlying assumption is based upon a flexible control plane and develops an application, which is able to migrate the network from one load status to another. The second assumption goes for full flexibility from scratch within definition of control plane architecture, intending to turn today's metro networks into a flexible platform for future services and applications.

  The findings will be applied to a virtual communication-based Internet of Things network.

The TANDEM project involves some academics (UR1, IMT, Stuttgart, Fraunhofer) and many industrials, among which we can cite Nokia, Orange, Thales, Vectrawave, Telenor. . . For more details see `https://www.celticplus.eu/project-sendate-tandem/`.

8.2 National Collaborations

- **Images & Réseaux Competitivity Cluster - ALAMO (2016-2018)**
  Participants: Olivier Berder, Matthieu Gautier, Baptiste Vrigneau, Mickaël Le Gentil
  ALAMO (Autonomous Long rAnge radio Modules for cOnnected farms) is a project that will allow farms to have a dedicated box to connect sensors with heterogeneous radio communications. The project involves Granit teams and two Small Medium Enterprises (SMEs): Euro-Process and CG-Wireless. The key features of the proposed system are optimized radio protocol, long range, low power consumption, providing a ready-to-use brick for integrator of digital solutions. Granit goal is to provide our skills on the energy management in sensor node and to address fundamental limits of long range communications.

- **Images & Réseaux Competitivity Cluster - Plug&Pos (2017-2019)**
  Participants: Olivier Berder, Antoine Courtay, Mickaël Le Gentil
  Plug&Pos is a project focused on indoor geolocation applied to museum applications. Challenges are to create an accurate indoor geolocation system and to propose interactive information on tablets to visitors. To achieve this aim, Granit team works on geolocation algorithms for facing to environment perturbations due to distance measuring with UWB radio. The first industrial partner is Ticatag for the prototyping phase and the second partner is Regard Services to propose contextual information with video, audio and augmented reality contents. The complete system must be installed quickly, support multi-users and be accurate with +/-20cm to differentiate nearby points of interest.

- **ANR PRCE - Wake-Up (2017-2020)**
  Participants: Olivier Berder, Antoine Courtay, Matthieu Gautier
  Using pure-asynchronous communication allowed by emerging Ultra-Low-Power (ULP) wake-up receivers (WUR), Wake-Up aims at proposing a low latency and energy efficient network architecture composed of heterogeneous radio nodes (long-range communication and ULP short-range WUR) with dedicated access and network protocols. A two-way cross layer optimization is envisaged in Wake-Up, since on one hand these heterogeneous network higher layers will take into account the specificities of the wake-up radio to optimize energy and latency, and on the other hand some recurrent application constraints will lead to specific wake-up radio designs. The consortium is composed of two academic partners (University of Rennes 1 and University of Strasbourg), one state-owned industrial and commercial establishment (CEA LETI) and one SME (Wi6Labs). The consortium will address these scientific challenges at both the node and the network levels, with controlled (FIT IoT Lab) and real-field experimental validations.

9 Dissemination

9.1 Scientific Responsibilities

- O. Berder is a member of the Editorial Board of International Journal of Distributed Sensor Networks
- O. Berder is in charge of Embedded Systems theme of the GIS ITS (Scientific Interest Group on Intelligent Transportation Systems)
- O. Berder is a member of the Organization Committee of the annual colloquium Energ&TIC, Pleumeur-Bodou
- O. Berder was a member of Technical Program Committee of IEEE PIMRC and is a reviewer for IEEE TSP, TWC, ToN, JSAC, ICC, GLOBECOM
- O. Berder served as a reviewer for the PhD of Ahmed Tauseef, *Radio Spectrum and Power Optimization Cognitive Techniques for Wireless Body Area etworks*, defended at Tallinn University of Technology, Estonia, June 26^{th} 2017
- O. Berder served as a reviewer for the PhD of Wissem Benali, *Modélisation et optimisation énergétique d'une chaîne de communication WiFi*, defended at Orange Labs, October 17^{th} 2017
- O. Berder served as the president of the jury for the PhD defense committee of Calypso Barnes, *Vérification et Validation de Propriétés de Protocoles pour Réseaux de Capteurs sans Fil grâce au Couplage de la Simulation et de l'Emulation du Système*, University of Côte d'Azur, June 28^{th} 2017
- O. Berder served as a member of the jury for the PhD defense of Ahmed Abdmouleh, *Non-binary LDPC codes associated to high-order modulations*, defended at University of Bretagne Sud, September 12^{th} 2017
- O. Berder and M. Gautier are elected members of Research Commission of IUT Lannion
- A. Courtay served as a reviewer for IJDSN, PIMRC.
- M. Gautier was a member of technical program committee of IEEE ISWCS, IEEE PIMRC, IARIA SENSORCOM and EAI CROWNCOM.
- M. Gautier served as a reviewer for Eurasip JWCN, MDPI Sensors, Globecom.
- M. Gautier was a session chair of one session at IEEE ICC conference.
- B. Vrigneau served as a reviewer for IEEE Communications Letters, PIMRC, ISTC.
- B. Vrigneau was a member of technical program committee of IEEE PIMRC

9.2 Involvement in the Scientific Community

- O. Berder and M. Gautier are elected members of Research Commission of IUT Lannion
- O. Berder, A. Courtay and M. Le Gentil did a demonstration of the Zyggie platform for BoWI project. "Zyggie: Wireless Sensor Node Prototype for Posture and Gesture Recognition", Technoference #20, February 2017
- M. Gautier presented the ALAMO project. "ALAMO project: the agricultural gateway", Technoference #21, June 2017
- O. Berder did a presentation on challenges in autonomous wireless sensors networks. M. Le Gentil did a demonstration of an energy harvesting manager based on fuzzy logic applied to wireless sensors networks. "To autonomous wireless sensors networks", Technoference #22, October 2017
- O. Berder and M. Gautier did a presentation entitled "Energy management in multi-hop WSN with energy harvesting: distributed processing and opportunistic protocol" during the "Near sensor computing" day, GDR SoC2, 8 novembre 2017

9.3 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 1.

- D.Demigny is a Vice-President of the University of Rennes 1, in charge of Digital Activities.
- D. Demigny is the Head of the Physical Measurements Department at IUT Lannion.
- P. Scalart is the Head of the Electronics Engineering department of ENSSAT.
- A. Courtay is supervising the first year students of the Electronics Engineering department of ENSSAT.
- M. Gautier is member of the French National University Council since 2015 in signal processing and electronics (Conseil National des Universités en 61e section).
- O. Berder is in charge of Studies Pursuit of Physical Measurements Department at IUT Lannion.
- O. Berder and B. Vrigneau are elected members of IUT Institute Council and Direction Committee.
- B. Vrigneau was in charge of student supervised project of Network and Communications department (January to August).

9.4 Teaching

- O. Berder: signal processing, 70h, IUT Lannion (L2)
- O. Berder: sensors and control, 90h, IUT Lannion (L2)
- O. Berder : digital systems, 80h, IUT Lannion (L1)
- A. Courtay: digital electronics, 122h, ENSSAT (L3)
- A. Courtay: digital system design, 12h, ENSSAT (L3)
- A. Courtay: PCB conception, 14h, ENSSAT (L3)
- A. Courtay: digital electronics communication interfaces, 68h, ENSSAT (M1)
- A. Courtay: digital electronics: Laser diode driver, 16h, 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)
- 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, 20h, ENSSAT (M2)

- R. Gerzaguet: System On Chips, 22h, ENSSAT (M2)
- B. Vrigneau: computer architecture, 14h, IUT Lannion (L1)
- B. Vrigneau: enterprise telephony, 20h, IUT Lannion (L1)
- B. Vrigneau: maths, 24h, IUT Lannion (L2)
- B. Vrigneau: telecommunications, 190h, IUT Lannion (L1, L2, L3)
- B. Vrigneau: data acquisition, 25h, University of Science and Technology of Hanoi (M1)

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