RESEARCH CENTRE

Inria Lyon Centre

IN PARTNERSHIP WITH:

Institut national des sciences appliquées de Lyon

2023

ACTIVITY REPORT

Project-Team

MARACAS

Models and Algorithms for Reliable Communication Systems

IN COLLABORATION WITH: Centre of Innovation in Telecommunications and Integration of services

DOMAIN

Networks, Systems and Services, Distributed Computing

THEME

Networks and Telecommunications

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Creation of the Project-Team: 2020 January 01

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2 Overall objectives

2.1 Motivation

During the last century, the industry of communications was devoted to improving human connectivity, leading to a seamless worldwide coverage to cope with increasing data rate demands and mobility requirements. The Internet revolution drew on a robust and efficient multi-layer architecture ensuring end-to-end services. In a classical network architecture, the different protocol layers are compartmentalized and cannot easily interact. For instance, source coding is performed at the application layer while channel coding is performed at the physical (PHY) layer. This multi-layer architecture blocked any attempt to exploit low level cooperation mechanisms such as relaying, phy-layer network coding or joint estimation. During the last decade, a major shift, often referred to as *the Internet of Things (IoT)*, was initiated toward a machine-to-machine (M2M) communication paradigm, which is in sharp contrast with classical centralized network architectures. The IoT enables machine-based services exploiting a massive quantity of data virtually spread over a complex, redundant and distributed architecture.

This new paradigm makes the aforementioned classical network architecture based on a centralized approach out-of-date.

The era of *Internet of Everything* deeply modifies the paradigm of communication systems. They have to transmute into reactive and adaptive intelligent systems, under stringent QoS constraints (latency, reliability) where the networking service is intertwined in an information-centric network. The associated challenges are linked to the intimate connections between communication, computation, control and storage. Actors, nodes or agents in a network can be viewed as forming a distributed system of computations—a *computing network*.

2.2 Scientific methodology

It is worth noting that working on these new architectures can be tackled from different perspectives, e.g. data management, protocol design, middleware, algorithmic design... Our main objective in Maracas is to address this problem from a communication theory perspective. Our background in communication theory includes information theory, estimation theory, learning and signal processing. Our strategy relies on three fundamental and complementary research axes:

- Mathematical modeling: information theory is a powerful framework suitable to evaluate the limits of complex systems and relies on probability theory. We will explore new bounds for complex networks (multi-objective optimization, large scale, complex channels,...) in association with other tools (stochastic geometry, queuing theory, learning,...)
- Algorithmic design: a number of theoretical results obtained in communication theory, despite their high potential are still far from a practical use. We will thus work on exploiting new algorithmic techniques. Back and forth efforts between theory and practice is necessary to identify the most promising opportunities. The key elements are related to the exploitation of feedbacks, signaling and decentralized decisions. Machine learning algorithms will be explored.
- Experimentation and cross-layer approach: theoretical results and simulation are not enough to provide proofs of concept. We will continue to put efforts on experimental works either on our own (e.g. FIT/CorteXlab and SILECS) or in collaboration with industries (Nokia, Orange, Thalès,...) and other research groups.

While our expertise is mostly related to the optimization of wireless networks from a communication perspective, the project of Maracas is to broaden our scope in the context of *Computing Networks*, where a challenging issue is to optimize jointly architectures and applications, and to break the classical network/data processing separation. This will drive us to change our initial positioning and to really think in terms of information-centric networks following, e.g. [**mao2017survey**, **li2018fundamental**, **yan2018storage**].

To summarize, *Computing Networks* can be described as highly distributed and dynamic systems, where information streams consist in a huge number of transient data flows from a huge number of nodes (sensors, routers, actuators, etc...) with computing capabilities at the nodes. These *Computing*

Networks are nothing but the invisible nonetheless necessary skeleton of cloud and fog-computing based services.

Our research strategy is to describe these *Computing Networks* as complex large scale systems in an information theory framework, but in association with other tools, such as stochastic geometry, stochastic network calculus, game theory [**m:quintero:hal-01397118**] or machine learning.

The multi-user communication capability is a central feature, to be tackled in association with other concepts and to assess a large variety of constraints related to the data (storage, secrecy,...) or related to the network (energy, self-healing,...).

The information theory literature or more generally the communication theory literature is rich of appealing techniques dedicated to efficient multi-user communications: e.g. physical layer network coding, amplify-and-forward, full-duplexing, coded caching at the edge, superposition coding. But despite their promising performance, none of these technologies play a central role in current protocols. The reasons are two-fold : i) these techniques are usually studied in an oversimplified theoretical framework which neglect many practical aspects (feedback, quantization,...), and that is not able to tackle large scale networks and ii) the proposed algorithms are of a high complexity and are not compatible with the classical multi-layer network architecture.

Maracas addresses these questions, leveraging on its past outstanding experience from wireless network design.

The aim of Maracas is to push from theory to practice a fully cross-layer design of *Computing Networks*, based on multi-user communication principles relying mostly on information theory, signal processing, estimation theory, game theory and optimization. We refer to all these tools under the umbrella of *communication theory*.

As such, Maracas project goes much beyond wireless networks. The *Computing Networks* paradigm applies to a wide variety or architectures including wired networks, smart grids, nanotechnology based networks. One Maracas research axis will be devoted to the identification of new research topics or scenarios where our algorithms and mathematical models could be useful.

3 Research program

3.1 General description

As presented in the first section, *Computing Networks* is a concept generalizing the study of multi-user systems under the communication perspective. This problematic is partly addressed in the aforementioned references. Optimizing *Computing Networks* relies on exploiting simultaneously multi-user communication capabilities, in the one hand, and storage and computing resources in the other hand. Such optimization needs to cope with various constraints such as energy efficiency or energy harvesting, delays, reliability or network load.

The notion of reliability (used in MARACAS acronym) is central when considered in the most general sense : ultimately, the reliability of a *Computing Network* measures its capability to perform its intended role under some confidence interval. Figure **??** represents the most important performance criteria to be considered to achieve reliable communications. These metrics fit with those considered in 5G and beyond technologies [**Sachs2018-5G**].

On the theoretical side, multi-user information theory is a keystone element. It is worth noting that classical information theory focuses on the power-bandwith tradeoff usually referred as Energy Efficiency-Spectral Efficiency (EE-SE) tradeoff (green arrow on **??**). However, the other constraints can be efficiently introduced by using a non-asymptotic formulation of the fundamental limits [**polyanskiy2010channel**, **tan2014asymptotic**] and in association with other tools devoted to the analysis of random processes (queuing theory, ...).

Maracas aims at studying *Computing Networks* from a communication point of view, using the foundations of information theory in association with other theoretical tools related to estimation theory and probability theory.

In particular, Maracas combines techniques from communication and information theory with statistical signal processing, control theory, and game theory. Wireless networks is the emblematic

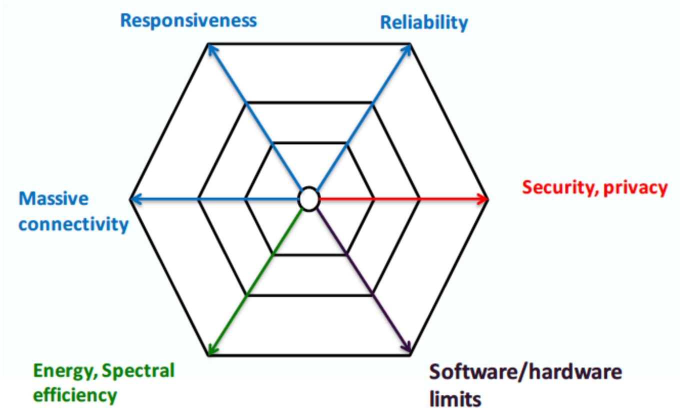

Figure 1: Main metrics for future networks (5G and beyond)

application for Maracas, but other scenarios are appealing for us, such as molecular communications, smart grids or smart buildings.

Several teams at Inria are addressing computing networks, but working on this problem with an emphasis on communication aspects is unique within Inria.

The complexity of *Computing Networks* comes first from the high dimensionality of the problem: i) thousands of nodes, each with up to tens setting parameters and ii) tens variable objective functions to be minimized/maximized.

In addition, the necessary decentralization of the decision process, the non stationary behavior of the network itself (mobility, ON/OFF Switching) and of the data flows, and the necessary reduction of costly feedback and signaling (channel estimation, topology discovering, medium access policies...) are additional features that increase the problem complexity.

The original positioning of Maracas holds in his capability to address three complementary challenges :

1. **to develop a sound mathematical framework inspired by information theory.**
2. **to design algorithms, achieving performance close to these limits.**
3. **to test and validate these algorithms on experimental testbeds.**

3.2 Research program

Our research is organized in 4 research axes:

- **Axis** 1 **- Fundamental Limits of Reliable Communication Systems**: Information theory is revisited to integrate reliability in the wide sense. The non-asymptotic theory which made progress recently and attracted a lot of interest in the information theory community is a good starting point. But for addressing computing network in a wide sense, it is necessary to go back to the foundation of communication theory and to derive new results, e.g. for non Gaussian channels [**m:egan2017capacity**] of for multi-constrained systems [**m:perlaza2018simultaneous**].

  This also means revisiting the fundamental estimation-detection problem [**vazquez2018saddlepoint**] in a general multi-criteria, multi-user framework to derive tractable and meaningful bounds.

  As mentioned in the introduction, *Computing Networks* also relies on a data-centric vision, where transmission, storage and processing are jointly optimized. The strategy of *caching at the edge* [**khoshkholgh2019caching**] proposed for cellular networks shows the high potential of considering simultaneously data and network properties. Maracas is willing to extend his skills on source coding aspects to tackle with a data-oriented modeling of *Computing Networks*.

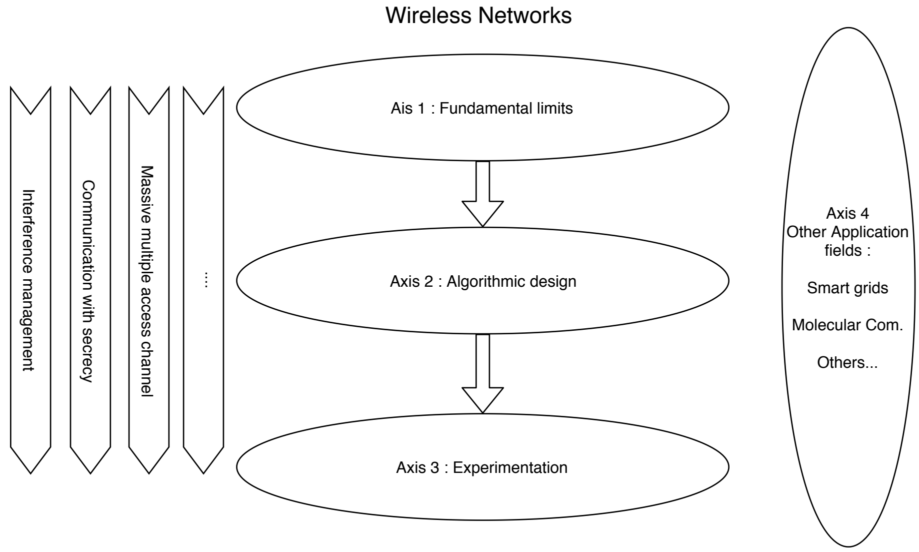

Figure 2: Maracas organization

- **Axis** 2 **- Algorithms and protocols**: Our second objective is to elaborate new algorithms and protocols able to achieve or at least to approach the aforementioned fundamental limits. While the exploration of fundamental limits is helpful to determine the most promising strategies (e.g. relaying, cooperation, interference alignment) to increase system performance, the transformation of these degrees of freedom into real protocols is a non trivial issue. One reason is the exponentially growing complexity of multi-user communication strategies, with the number of users, due to the necessity of some coordination, feedback and signaling. The general problem is a decentralized and dynamic multi-agents multi-criteria optimization problem and the general formulation is a non-linear and non-convex large scale problem.

  The conventional research direction aims at reducing the complexity by relaxing some constraints or by reducing the number of degrees of freedom. For instance, topology interference management is a seducing model used to reduce feedback needs in decentralized wireless networks leading to original and efficient algorithms [**yi2018topological**, **liu2018topological**].

  Another emerging research direction relies on using machine learning techniques [**dorner2018deep**] as a natural evolution of cognitive radio based approaches. Machine learning in the wide sense is not new in radio networks, but the most important works in the past were devoted to reinforcement learning approaches. The use of deep learning (DL) is much more recent, with two important issues : i) identifying the right problems that really need DL algorithms and ii) providing extensive data sets from simulation and real experiments. Our group started to work on this topic in association with Nokia in the joint research lab. As we are not currently expert in deep learning, our primary objective is to identify the strategic problems and to collaborate in the future with Inria experts in DL, and in the long term to contribute not only to the application of these techniques, but also to improve their design according to the constraints of computing networks.

- **Axis** 3 **- Experimental validation** : With the rapid evolution of network technologies, and their increasing complexity, experimental validation is necessary for two reasons: to get data, and to validate new algorithms on real systems.

  Maracas activity leverages on the FIT/CorteXlab platform (), and our strong partnerships with leading industry including Nokia Bell Labs, Orange labs, Sigfox or Sequans. Beyond the platform itself which offers a worldwide unique and remotely accessible testbed , Maracas also develops original experimentations exploiting the reproducibility, the remote accessibility, and the deployment facilities to produce original results at the interface of academic and industrial research [**m:alexandropoulos:hal-01395615**, **m:fadlallah:hal-01492353**]. FIT/CorteXlab uses the GNU Radio environment to evaluate new multi-user communication systems.

Our experimental work is developed in collaboration with other Inria teams especially in the Rhone-Alpes centre but also in the context of the future SILECS project which will implement the convergence between FIT and Grid'5000 infrastructures in France, in cooperation with European partners and infrastructures. SILECS is a unique framework which will allow us to test our algorithms, to generate data, as required to develop a data-centric approach for computing networks.

Last but not least, software radio technologies are leaving the confidentiality of research laboratories and are made available to a wide public market with cheap (few euros) programmable equipment, allowing to setup non standard radio systems. The existence of home-made and non official radio systems with legacy ones could prejudice the deployment of Internet of things. Developing efficient algorithms able to detect, analyse and control the spectrum usage is an important issue. Our research on FIT/CorteXlab will contribute to this know-how.

- **Axis** 4 **- Other application fields** : Even if the wireless network context is still challenging and provides interesting problems, Maracas targets to broaden its exploratory playground from an application perspective. We are looking for new communication systems, or simply other multi-user decentralized systems, for which the theory developed in the context of wireless networks can be useful. Basically, Maracas might address any problem where multi-agents are trying to optimize their common behavior and where the communication performance is critical (e.g. vehicular communications, multi-robots systems, cyberphysical systems). Following this objective, we already studied the problem of missing data recovery in smart grids [**m:genes2018robust**] and the original paradigm of molecular communications [**m:egan:hal-01928205**].

  Of course, the objective of this axis is not to address random topics but to exploit our scientific background on new problems, in collaboration with other academic teams or industry. This is a winning strategy to develop new partnerships, in collaboration with other Inria teams.

4 Application domains

4.1 5G, 6G, and beyond

The fifth generation (5G) broadens the usage of cellular networks but requires new features, typically very high rates, high reliability, ultra low latency, for immersive applications, tactile internet, M2M communications.

From the technical side, new elements such as millimeter waves, massive MIMO, massive access are under evaluation. The initial 5G standard validated in 2019, is finally not really disruptive with respect to the 4G and the clear breakthrough is not there yet. The ideal network architecture for billions of devices in the general context of Internet of Things, is not well established and the debate still exists between several proposals such as NB-IoT, Sigfox, Lora. We are developing a deep understanding of these techniques, in collaboration with major actors (Orange Labs, Nokia Bell Labs, Sequans, Sigfox) and we want to be able to evaluate, to compare and to propose evolutions of these standards with an independent point of view.

This is why we are interested in developing partnerships with major industries, access providers but also with service providers to position our research in a joint optimization of the network infrastructure and the data services, from a theoretical perspective as well as from experimentation.

4.2 Energy sustainability

The energy footprint and from a more general perspective, the sustainability of wireless cellular networks and wireless connectivity is somehow questionable.

We develop our models and analysis with a careful consideration of the energy footprint : sleeping modes, power adaptation, interference reduction, energy gathering, ... many techniques can be optimized to reduce the energetic impact of wireless connectivity. In a *computing networks* approach, considering simultaneously transmission, storage and computation constraints may help to reduce drastically the overall energy footprint.

4.3 Smart building, smart cities, smart environments

Smart environments rely on the deployment of many sensors and actuators allowing to create interactions between the twinned virtual and real worlds. These smart environments (e.g. smart building) are for us an ideal playground to develop new models based on information theory and estimation theory to optimize the network architecture including storage, transmission, computation at the right place.

Our work can be seen as the invisible side of cloud/edge computing. In collaboration with other teams expert in distributed computing or middleware (typically at CITIlab, with the team Dynamid of Frédéric Le Mouel) and in the framework of the chaire SPIE/ICS-INSA Lyon, we want to optimize the mechanisms associated to these technologies : in a multi-constrained approach, we want to design new distributed algorithms appropriate for large scale smart environments.

From a larger perspective we are interested on various applications where the communication aspects play an important role in multi-agent systems and target to process large sets of data. Our contribution to the development of TousAntiCovid falls into this area.

4.4 Machine learning based radio

During the first 6G wireless meeting which was held in Lapland, Finland in March 2019, machine learning (ML) was clearly identified as one of the most promising breakthroughs for future 6G wireless systems expected to be in use around 2030 (SNS 6G IA Horizon Europe). The research community is entirely leveraging the international ML tsunami. We strongly believe that the paradigm of wireless networks is moving toward to a new era. Our view is supported by the fact that artificial Intelligence (AI) in wireless communications is not new at all. The telecommunications industry has been seeking for 20 years to reduce the operational complexity of communication networks in order to simplify constraints and to reduce costs on deployments. This obviously relies on data-driven techniques allowing the network to self-tune its own parameters. Over the successive 3GPP standard releases, more and more sophisticated network control has been introduced. This has supported increasing flexibility and further self-optimization capabilities for radio resource management (RRM) as well as for network parameters optimization.

We target the following key elements :

- Obtaining data from experimental scenarios, at the lowest level (baseband I/Q signals) in multi-user scenarios (based upon FIT/CorteXlab).
- Developing a framework and algorithms for deep learning based radio.
- Developing new reinforcement learning techniques in high dimensional state-action spaces.
- Embedding NN structures on radio devices (FPGA or m-controllers) and in FIT/CorteXlab.
- Evaluating the gap between these algorithms and fundamental limits from information theory.
- Building an application scenario in a smart environment to experiment a fully cross-layer design (e.g. within a smart-building context, how could a set of object could learn their protocols efficiently ?)

4.5 Molecular communications

Many communication mechanisms are based on acoustic or electromagnetic propagation; however, the general theory of communication is much more widely applicable. One recent proposal is molecular communication, where information is encoded in the type, quantity, or time or release of molecules. This perspective has interesting implications for the understanding of biochemical processes and also chemical-based communication where other signaling schemes are not easy to use (e.g., in mines). Our work in this area focuses on two aspects: (i) the fundamental limits of communication (i.e., how much data can be transmitted within a given period of time); and (ii) signal processing strategies which can be implemented by circuits built from chemical reaction-diffusion systems.

A novel perspective introduced within our work is the incorporation of coexistence constraints. That is, we consider molecular communication in a crowded biochemical environment where communication should not impact pre-existing behavior of the environment. This has lead to new connections with communication subject to security constraints as well as the stability theory of stochastic chemical reaction-diffusion systems and systems of partial differential equations which provide deterministic approximations.

5 Social and environmental responsibility

5.1 Footprint of research activities

Considering our research activities, most of our works are based on theoretical works or simulations. We may be concerned with the following aspects :

- Experimental works : To reduce the energy footprint of CorteXlab, all equipments are connected on Electronic Power Switches (EPS) with remote access. Then, the equipments can be turned on only when an experiment is launched.
- Computer sustainability : We use to keep the computers for at least 4 years, to avoid a fast turn-over.
- Travelling represents an important part of our CO2 footprint. For 2020, most of travels have been cancelled. In the future we believe that international events remain important for young researchers, but we will start a reflexion on this question.

5.2 Impact of research results

Our research may impact the energy consumption of the digital world even if the current debate on 5G is ill-posed. It is worth that the rebound effect associated to any technology should be thought carrefully.

Typially, the desing of former wireless protocols focused on high rates and high quality of service, with a lack of considering energy and CO_2 footprint.

In the future, we will contribute to better understanding large scale impact of new communication technologies, and to investigate how innovation can help reducing the energy footprint, and may help to build a greener world.

6 Highlights of the year

6.1 Awards

- Maxime Guillaud is a Distinguished Lecturer of the IEEE Communications Society for the period 2023-2024.
- Mathieu Goutay got the best PhD award in the field of computer sciences at INSA Lyon (dec, 2023).
- The paper [**seddik:hal-04184112**] co-authored by Maxime Guillaud received the best paper award at the Thirty-Ninth Conference on Uncertainty in Artificial Intelligence, Pittsburgh, PA (USA).

6.2 New European projects

- Maxime Guillaud is co-PI of the project CHASER (Chist-ERA program, call 2022). This project deals with the development of channel charting as a Service, and falls in the area of Joint Communication and Sensing.
- Maxime Guillaud and Jean-Marie Gorce are co-PIs of the INSTINCT project funded by Hoprizon Europe in ths SNS 6G-IA program. The project deals with the design of new waveforms for joint communication and sensing, and will also involve Cyrille Morin and Léonardo S. Cardoso.

6.3 National strategy

- Maracas is involved in 3 projects of the PEPR Networks of the Futu(PEPR-NF): the project PERSEUS on cell-free in sub-millimetric frequency range, the project FOUNDS on fundamental limits of networks and the project NF-Plateforme XG which develops the experimental platform for the PEPR. As such, this testbed is also part of the European SLICES ESFRI program.

6.4 Permanent positions filled

- In 2023, the group was happy to welcome a new senior researcher, Dr Maxime Guillaud. His activity covers massive access related topics, including tensor representations, as well as joint communication and sensing topics.
- A new permanent research engineer, Dr Cyrille Morin, expert in machine learning for radio systems and related software development.

7 New software, platforms, open data

The main contribution in software is relative to the development of software tools for the use of CorteXlab to evaluate real systems. The Wiki tracks all the recent results and available tutorials CorteXlab wiki.

The three most recent tutorials are:

- S3_CAP, a modular framework for slotted transmission is a framework allowing to emulate random access policies in CorteXlab S3_CAP tutorial
- Tutorial 6 proposes a new framework to generate databases with multiple receivers to test learning techniques on real modulated signals. It can be used for Tx identification, modulation identification, signal detection, ... Creating Datasets for Fingerprinting
- When CorteXlab meets AFF3CT. AFF3CT is a new library (AFF3CT) developed by the Inria Bordeaux, LABRI, INP ans associated partners. With the help of ADrien Cassagne, we deployed AFF3CT in a Docker module allowing to deploy and to test AFF3CT in CorteXlab. This tutorial provides this Docker and helps the user to run AFF3CT in CorteXlab.

7.1 New software

7.1.1 cortexlab-minus

Keywords: Experimentation, SDR (Software Defined Radio)

Functional Description: Minus is an experiment control system able to control, the whole lifecycle of a radio experiment in CorteXlab or any other testbed inspired by it. Minus controls and automates the whole experiment process starting from node power cycling, experiment deployment, experiment start and stop, and results collection and transfer. Minus is also capable of managing multiple queues of experiments which are executed simultaneously in the testbed.

Contact: Matthieu Imbert

7.1.2 cortexlab-webapp

Keywords: Experimentation, SDR (Software Defined Radio)

Functional Description: The cortexlab web application, which aims at easing platform usage and improving the metadata that we can associate with each experimenter and experiment. This metadata aims at improving the metrics we can gather about the platform's usage The cortexlab web application provides several modules and workflows : - a user management module that allows users to manage their account with a graphical interface. This module also contains two administrator workflows: one to import several user accounts, at the same time, from a json file, which is useful for many use cases, and one to request users to re-validate their accounts, if, for example, the expiration date is outdated, - a booking module: it allows users to book the test bed with a user-friendly graphical interface, instead of the command line. It also allows the user to manage their reservations, - a security module. - a statistics module (developped in 2023) which provides some metrics like the calcul of occupancy and usage ratios on a user selected period.

Contact: Pascal Girard

Partner: Insa de Lyon

7.1.3 Cortexlab_LORA_PHY

Name: Multi nodes LORA in GNU radio

Keywords: CorteXlab, GNU Radio, LoRaWAN

Functional Description: Dynamic and customizable LoRa physical layer, derived from the original EPFL LoRa implementation in GNU Radio. More information on this implementation can be found in "Dynamic LoRa PHY layer for MAC experimentation using FIT/CorteXlab testbed", written by Amaury Paris, Leonardo S. Cardoso and Jean-Marie Gorce.

This adaptation allows end-users to connect any existing upper layer to the physical layer through an easy to use interface using the JSON format, without having to implement the upper layer in GNU Radio.

URL: `https://github.com/AmauryPARIS/LoRa_PHY_Cxlb/`

Contact: Leonardo Sampaio

7.1.4 CorteXlab-IoT Framework

Name: Framework for PHY-MAC layers Prototyping in Dense IoT Networks using CorteXlab Testbed

Keywords: SDR (Software Defined Radio), Iot, CorteXlab, GNU Radio

Functional Description: This framework was developed in the project ”Enhanced Physical Layer for Cellular IoT” (EPHYL). It provides a customizable and open source design for IoT networks prototyping in a massive multi-user, synchronized and reproducible environment thanks to the hardware and software capabilities of the testbed. The framework has been extended in 2022, to improve modularity, with the project ADT 3D-SIP.

Release Contributions: Extension to improve synchronization problems, and to support modularity. Independent optimization and development of the PHY layer, the MAC layer and the radio resource management algorithms.

URL: `https://github.com/AmauryPARIS/gr-ephyl`

Publication: hal-02150687

Author: Othmane Oubejja

Contact: Jean-Marie Gorce

7.2 New platforms

Participants: Pascal Girard, Jean-Marie Gorce, Maxime Guillaud, Mathieu Imbert, Cyrille Morin, Léonardo Sampaio Cardoso.

Figure 3: FIT/CorteXlab facility

7.2.1 FIT/CorteXlab toward integration in SLICES/Europe

FIT (Future Internet of Things) was a french Equipex (Équipement d'excellence) built to develop an experimental facility, a federated and competitive infrastructure with international visibility and a broad panel of customers. FIT is composed of four main parts: a Network Operations Center (FIT NOC), a set of IoT test-beds (FIT IoT-Lab), a set of wireless test-beds (FIT-Wireless) which includes the FIT/CorteXlab platform managed by Maracas team, and finally a set of Cloud test-beds (FIT-Cloud). In 2014 the construction of the room was done and SDR nodes have been installed in the room: 42 industrial PCs (Aplus Nuvo-3000E/P), 22 NI radio boards (usrp) and 18 Nutaq boards (PicoSDR, 2x2 and 4X4) can be programmed remotely, from internet now.

As the FIT project development phase ended in 2019 , CorteXlab has seen continued usage as well as further developments. FIT/CorteXlab has been used by both INSA and the European GNU Radio Days (Gnu radio days) for both lectures and tutorials. Several scientific measurements campaigns have taken place in the FIT/CorteXlab experimentation room and are under works at the moment.

In 2023, CorteXlab has been integrated in the roadmap of the PEPR-NF plateform project and will be funded for a renew of the full infrastructure, in coordination with Raymond Knopp from Eurecom, and Walid Dabbous from the team DIANA, Inria Sophia. The new deployment is expected by the end of 2024.

8 New results

As presented is section **??**, the research program of MARACAS focuses on reliable communications for multi-user systems, in the context of computing networks. The project is organized in four axes : i) fundamental limits of multi-user systems, ii) algorithms for efficient multi-user systems, iii) experimentation and iv) cross-roads exploration as detailed in section **??**. However the research in MARACAS is not siloed. Typically a specific scenario (e.g. Grant free multiple access) is studied from theory to experimentation. To highlight these interactions between the different axes, the results are not presented per axis, but from an applicative perspective.

But, before describing these reference scenarios, it is worth highlighting the evolution of our methods and tools in each of the axes.

- Axis 1 : to evaluate the fundamental limits of multi-user systems we address the following topics: i) Malcolm Egan and Jean-Marie Gorce worked on finite blocklength information theory with an extension to heterogeneous arrivals and deadlines, to develop protocols for real-time or high reliability constraints. ii) Because the new technologies rely on a huge increase of dimensions such as multi-technologies, multi-frequencies, multi-antennas, cell-free, the optimization problems associated to these multi-user technologies become more and more complex. To address these problems in large dimension, Maxime Guillaud develops new models based on random tensors and random matrices. Malcolm Egan also contributes to the development of new communication models in the context of goal oriented communications.

- Axis 2 : These multi-user communications are complex scenarios for which channel coding, resource allocation, scheduling and coordination are complex problems instanciated in many wireless protocols : cellular networks, WiFi, Lora. But the known solutions are not optimal, their complexity grows exponentially with the number of users or the number of messages.

  Model-based aproaches are developed with tools such as Bayesian estimation or message passing algorithms. In this area we develop signal processing techniques and resource allocation algorithms taking into account heterogeneous and correlated user activity. The idea is to adapt the protocols to some specific properties of data sources.

  In many problems however, model-based solutions are not able to handle the increasing complexity of modern systems. We study new concepts such as protocol learning or channel charting.

  Beyond machine learning, another line of research is to exploit quantum algorithms to solve complex problems such as multi-user detection.

  From an application perspective, we also develop new activities in the field of joint communication and sensing, that is one of the hot topic for 6G. Two techniques are currently screened in MARACAS : Channel charting and zero-energy TAGs.

- Axis 3 concerns technical developments including experimentation as well as new technolgoy design. Our flagship platform is CorteXlab on which Cyrille Morin and Léonardo Cardoso worked on the development of new databases for modulated signals identification. Cyrille Morin also supervised Chang Mu to integrate the library AFF3CT (AFF3CT) in CorteXlab, see when AFF3CT meets CorteXlab. In addition with the project U-WAKE Guillaume Marthe explores the use of Spiking Neurons to design new wake-up radios with performance guarantees.

- Axis 4 is devoted to crossroads exploration. We contributed on predictive maintenance with a joint optimization of communication and computing (closely related to axis 2). The development of quantum algorithms started in this axis and is now integrated in axis 2. We also explore in the U-WAKE project, the use of spiking neurons (in connection with axis 2). An important line of work is related to molecular communications (where theoretical tools from axis 1 and axis 2 are used).

The reference scenarios highlight the increasing intertwin between data processing (computing) and data transmission (communication). This leads us to extend our research to topics going beyond communications (data models, correlation in user activities, goal oriented communications, channel charting, communication and sensing).

8.1 Random and massive access for IoT

Participants: Léonardo Cardoso, Lelio Chetot, Malcolm Egan, Jean-Marie Gorce, Claire Goursaud, Maxime Guillaud, Alix Jeannerot, Shashwat Mishra, Mateus Pontes Mota.

In the context of IoT, a critical problem is to be able to serve many users, having each a low probability of transmission. The problem appears in the downlink as well as in the uplink but the problems in terms of signaling are different. This research axis is lead by Jean-Marie Gorce, but all Maracas members have contributions around this scenario. This topic is covered in axes 1, 2 and 3. We present below the results of the year.

In [**mishra:hal-04360320**], we propose a framework for maximizing the number of machine-type devices connected in the uplink of a Narrowband Internet of Things (NB-IoT) network using non-orthogonal multiple access (NOMA). The system is based on the fast-uplink grant (FUG), where the base station (BS) schedules the access for active devices requesting connection. This problem is a mixedinteger non-convex problem and real-time solutions using general solvers are computationally prohibitive. The proposed scheduling solution comprises efficient device clustering and optimum power allocation using a bipartite graph matching approach, termed connection throughput maximizing full matching with pruning (CTMBM). Different from the other solutions of state-of-the-art, our proposed scheme considers scheduling over multiple transmission time intervals while considering the transmission deadlines and quality of service (QoS) for the devices. Additionally, we provide a method for priority scheduling of a subset of devices. We compare our solution to the state-of-the-art schemes and analyze the achieved gains through Monte-Carlo computer simulations.

An important part of the work elaborated with Lelio Chetot and Malcolm Egan, concerns the study of non independent and identical distributions of messages. We studied both transmission and reception strategies.

In [**chetot:hal-04151973**], we studied the context of Industrial IoT (IIoT) as it is one of the major verticals targeted by the next generations of wireless networks. In order to provide industrial plants with features relying on wireless communications, the grant-free RA (GFRA) protocol appears to be a promising means for supporting massive ultra-reliable connectivity; at the same time, it is a critical bottleneck that requires an access point (AP) to be able to jointly perform active user detection and channel estimation (AUDaCE) to fulfill its main mission of allowing industrial wireless devices to access the core network. This mission is even harder when the GFRA requests are correlated because of event-driven activity triggers. In this work, we propose a new tractable gaussian correlated activity (GCA) model for this scenario. The corresponding AUDaCE problem is then studied in the Bayesian compressed sensing (BCS) framework. An hybrid instance of the generalized AMP (GAMP) algorithm is derived and its capability to perform AUDaCE is numerically assessed by extensive Monte-Carlo simulations. The numerical results show gains of 2.5dB in channel estimation gain for twice less detection errors w.r.t. state-of-theart algorithms.

But in grant-free random access, another key question is how devices should utilize resources without coordination. One standard solution to this problem are strategies where devices randomly select time-slots based on an optimized stochastic allocation rule. However, the optimization of this allocation rule requires accurate knowledge of which devices have been active in previous frames. As user identification algorithms are subject to errors, the expected throughput of the optimized allocation can be highly sub-optimal. In [**jeannerot:hal-04114547**, **jeannerot:hal-04257479**, **jeannerot:hal-04130618**], we propose algorithms for optimization of device time-slot allocations that mitigate the impact of user identification errors. We show that when the activity distribution with and without errors is known, then our algorithm converges with probability one to a stationary point. When the activity distributions are not available, we introduce new theoretically-motivated heuristics which significantly improve the expected throughput over existing algorithms and approach the performance when errors are not present.

8.2 Heterogeneous time constraints : fundamental limits

Participants: Malcolm Egan, Jean-Marie Gorce, Homa Nikbakht.

This line of research is lead by Jean-Marie Gorce and contributes to axis 1 and axis 2. The objective is to extend information theory to explore the fundamental limits of communications under heterogeneous time constraints.

A standard assumption in the design of ultra-reliable low-latency communication systems is that the duration between message arrivals is larger than the number of channel uses (in the information theory wording, a c.u. corresponds to one transmission symbol), before the decoding deadline. Nevertheless, this assumption fails when messages arrive rapidly and reliability constraints require that the number of channel uses exceed the time between arrivals. In [**nikbakht:hal-04360147**], we consider a broadcast setting in which a transmitter wishes to send two different messages to two receivers over Gaussian channels. Messages have different arrival times and decoding deadlines such that their transmission windows overlap. For this setting, we propose a coding scheme that exploits Marton's coding strategy. We derive rigorous bounds on the achievable rate regions. Those bounds can be easily employed in point-to-point settings with one or multiple parallel channels. In the point-to-point setting with one or multiple parallel channels, the proposed achievability scheme outperforms the Normal Approximation, especially when the number of channel uses is smaller than 200. In the broadcast setting, our scheme agrees with Marton's strategy for sufficiently large numbers of channel uses and shows significant performance improvements over standard approaches based on time sharing for transmission of short packets.

In [**nikbakht:hal-04360312**] we explore how random user activities and heterogeneous delay traffic can be taken into account to design efficient coding schemes and information-theoretic converse results. The heterogeneous traffic is composed of delay-tolerant traffic and delay-sensitive traffic where only the former can benefit from transmitter and receiver cooperation since the latter is subject to stringent decoding delays. The total number of cooperation rounds at transmitter and receiver sides is limited to D rounds. Each transmitter is active with probability $\rho \in [0,1]$. We consider two different models for the arrival of the mixed-delay traffic. We derive inner and outer bounds on the fundamental per-user multiplexing gain (MG) region of the symmetric Wyner network as well as inner bounds on the fundamental MG region of the hexagonal model. Our inner and outer bounds are generally very close and coincide in special cases.

8.3 Goal oriented communications

Participants: Malcolm Egan, Jean-Marie Gorce, Naveed Ahmad.

This line of research is lead by Malcolm Egan and covers axis 1 and axis 2. This research is in line with join communication and computing, in the context of goaol oriented communications. Since a receiver aims at computing a function, the objective is to learn simultaneously the encoding procedures and the classification function.

With the proliferation of cheap sensors and the ubiquity of cloud and edge computing, predictive/condition-based maintenance is expected to play an important role in smart homes and buildings. Nevertheless, a key difficulty is ensuring that sensors provide data of sufficient quality in order to reliably detect building (e.g., heating system) degradation in systems or comfort. At the same time, sensor utilization should be limited as much as possible in order to minimize power consumption and increase the lifetimes of batteries. A solution to this problem requires careful codesign of sensor communication and data analytics. In [**ahmad:hal-04361059**, **ahmad:hal-04361063**], we introduce a formulation of this codesign problem, which is based on an optimization problem to jointly design how often data is collected and compression levels in order to balance the quality of fault detection with the quantity of transmitted data. To solve the optimization problem, we apply a differentiable search algorithm based on a variant of stochastic gradient descent for discrete optimization problems. We apply our codesign framework and solve the resulting optimization problem using data obtained from a building comfort experiment known as the Twin House Experiment. We also provide an extension of our algorithm to a dynamic variant of the codesign framework, where comfort levels and power consumption penalties are time varying. Numerical results show that our algorithm rapidly finds an efficient tradeoff between classifier accuracy and sensor power consumption.

8.4 Random tensors : from theory to applications in communications

Participants: Maxime Guillaud.

This line of research is lead by Maxime Guillaud and covers axis 1 and axis 2. Although the papers described below are more theoretic and cover general data analysis problems, their application is important in various communication problems such as massive access or channel charting.

In [**seddik:hal-04102861**], asymmetric order$-d$ spiked tensor models with Gaussian noise are studied, relying on random matrix theory (RMT). Using the variational definition of the singular vectors and values of (Lim, 2005), we show that the analysis of the considered model boils down to the analysis of an equivalent spiked symmetric block-wise random matrix. Our approach allows the exact characterization of the almost sure asymptotic singular value and alignments of the corresponding singular vectors with the true spike components. In contrast to other works that rely mostly on tools from statistical physics to study random tensors, our results rely solely on classical RMT tools such as Stein's lemma. Finally, classical RMT results concerning spiked random matrices are recovered as a particular case. Then, [**seddik:hal-04076864**, **seddik:hal-04271959**] study the deflation algorithm when applied to estimate a low-rank symmetric spike contained in a large tensor corrupted by additive Gaussian noise. Specifically, we provide a precise characterization of the large-dimensional performance of deflation in terms of the alignments of the vectors obtained by successive rank-1 approximation and of their estimated weights, assuming non-trivial (fixed) correlations among spike components. Our analysis allows an understanding of the deflation mechanism in the presence of noise and can be exploited for designing more efficient signal estimation methods. [**seddik:hal-04184112**] provides a theoretical analysis of learning from data that have an underlying low-rank tensor structure in both supervised and unsupervised settings, under a simplified data model. For the supervised setting, we provide an analysis of a Ridge classifier (with high regularization parameter) with and without knowledge of the low-rank structure of the data. Our results quantify analytically the gain in misclassification errors achieved by exploiting the low-rank structure for denoising purposes, as opposed to treating data as mere vectors. We further provide a similar analysis in the context of clustering, thereby quantifying the exact performance gap between tensor methods and standard approaches which treat data as simple vectors.

8.5 Neural networks, communication and energy efficiency

Participants: Malcolm Egan, Claire Goursaud, Guillaume Marthe.

All Maracas permanent members have some works related to the use of Deep Neural Networks (DNN). Indeed, using DNN for some difficult tasks to be done in communications is quite standard and is one of the keystones elements for 6G. We may use machine learning for channel charting, for terminal identification, for sensing, for coding, etc... In this section we present two line of research devoted to the design of NN based solutions and focusing and energy efficiency. The first part study the DNN architecture itself and the second proposed the use of spike neurons for wake-up radio.

8.5.1 Energy efficiency

This evaluation has been performed with the team AGORA and in the framework of the chaire INSA with SPIE/ICS. The MARACAS contribution is lead by Malcolm Egan. The training energy efficiency of deep neural networks became an extensively studied research topic in the last years. Some of the existing approaches seek to reduce the size of the architecture by either starting the training with a large network and pruning it, or by beginning with a seed architecture and then growing it. Instead of compressing the architecture, other approaches aim to reduce the number of training examples through data selection. While various approaches belonging to these two categories have been proposed, only a few works actually conduct energy measurements. Others merely mention potential gains in efficiency or rely on alternative evaluation metrics such as FLOPs. In [**boumendil:hal-04282146**], we conduct a series of experiments both on a synthetic dataset and on image classification benchmarks in order to compare the impact of pruning, architecture growing and data selection on training energy consumption and prediction quality. Our results show that growing maintains a high prediction quality but brings limited energy gains when the size of the resulting architecture is large. Pruning can offer high gains, but also impacts accuracy, making it more suited for large models. Data selection provides energy gains correlated with the selectivity rate but causes an accuracy loss. We find that the effectiveness of every technique depends on its hyperparameters and on the architecture size.

8.5.2 Spiking neurons for wake-up radio

This research is lead by Claire Goursaud and is more connected to axis 2.

Energy consumption remains the main limiting factors in many IoT applications. In particular, microcontrollers consume far too much power. In order to overcome this problem, new circuit designs have been proposed and the use of spiking neurons and analog computing has emerged as it allows a very significant consumption reduction. However, working in the analog domain brings difficulty to handle the sequential processing of incoming signals as is needed in many use cases. In [**marthe:hal-04244910**, **marthe:hal-04182362**], we use a bio-inspired phenomenon called Interacting Synapses to produce a time filter, without using non-biological techniques such as synaptic delays. We propose a model of neuron and synapses that fire for a specific range of delays between two incoming spikes, but do not react when this Inter-Spike Timing is not in that range. We study the parameters of the model to understand how to choose them and adapt the Inter-Spike Timing. The originality of our work is to propose a new way, in the analog domain, to deal with temporal sequences.

Because these Spiking neurons are energy efficient, they could be useful in the context of Internet of Things (IoT), where energy consumption is a critical issue. This is the reason why many research projects focus on Wake-up Radio (WuR) receivers that permit the nodes to remain in sleep mode for as long as possible and to wake them up only if needed. However, current WuR use classic microcontrollers that are still too energy consuming. Thus, in [**marthe:hal-04115278**, **marthe:hal-04090633**], we propose to adapt spiking neurons based NN as a wake-up radio receiver. We aim at waking up the concerned node by recognising one or many activation sequences in a bit flow. We propose here a configuration for the neurons along with the design of appropriate sequences. We present the performances of our system and the impact of different parameters on the accuracy of the recognition system.

8.6 Quantum networks and communications

Participants: Claire Goursaud, Fabrice Dupuy, Muhammad Idham Habibie, Romain Piron.

This line of research is lead by Claire Goursaud and covers axis 2 and axis 4. The objective is to bridge the gap between network protocol design and quantum algorithms, assuming that in the future, some equipment could host a quantum computer. We explore how such equipement could improve the complexity of some protocols.

In [**dupuy:hal-04244891**], the key challenges (loss due to distance, entanglement routing, multi-commodities) for the coming quantum internet, relying on entanglement of quantum bits (for short, qubits) on top of an existing network, are analyzed. A unifying framework enabling to compare the various entanglement distribution, purification, and routing protocols published so far is presented. With regard to entanglement routing, the introduction of different time windows will be essential in order to cope efficiently with the main challenges like complex route calculation and fidelity estimation on the one hand, actual entanglement route selection and entangled photon generation on the other hand. For a roll-out on top of existing transmission networks, all the research publications for the last 20 years start to cover pretty well the global scheme. Nevertheless, open questions remain, like the actual advantage of some task execution prior to the online quantum path selection, or the design of algorithms approximating the multi-commodities flow optimization problem, or the issue of dealing with a processing time not much longer than the qubit life time.

Multi-user detection with Grover's algorithm

To support multiple transmissions in an optical fiber, several techniques have been studied, such as code division multiple access (OCDMA). In particular, non-coherent OCDMA systems are appreciated for their simplicity. However, they suffer from multiple access interference (MAI), which degrades performance. In order to deal with this MAI, several detectors have been studied. Among them, Maximum Likelihood (ML) is the best. But it is very expensive because it requires testing all possibilities before making a decision. However, thanks to recent advances in quantum computing, this complexity problem can be circumvented. Indeed, quantum algorithms, such as Grover, exploit superposition states in the quantum domain and make it possible to accelerate calculation. Thus, in [**habibie:hal-04244903**], we propose to adapt Grover's quantum algorithm in the context of multi-user detection, in an OCDMA system using non-orthogonal codes. We present a way to adapt the received noisy signal to the constraints defined by the Grover algorithm, and then evaluate the probability of success of the quantum receiver. We show the advantages of our proposal compared to the classical detector and the optimal ML detector.

8.7 On channel charting

Participants: Maxime Guillaud, Yamil Vindas.

This research is lead by Maxime Guillaud and covers axes 1, 2 and 3. As detailed in [**ferrand:hal-04067052**], channel charting is a recently proposed framework that applies dimensionality reduction to channel state information (CSI) in wireless systems with the goal of associating a pseudo-position to each mobile user in a low-dimensional space: the channel chart. Channel charting summarizes the entire CSI dataset in a self-supervised manner, which opens up a range of applications that are tied to user location. In this article, we introduce the theoretical underpinnings of channel charting and present an overview of recent algorithmic developments and experimental results obtained in the field. We furthermore discuss concrete application examples of channel charting to network- and user-related applications, and we provide a perspective on future developments and challenges as well as the role of channel charting in next-generation wireless networks.

CC can be applied at the infrastructure basestation side with the goal of extracting pseudo-position information for each user. In [**taner:hal-04325927**], we focus on the practically relevant streaming CSI data scenario, in which CSI is constantly estimated. To deal with storage limitations, we develop a novel streaming CC architecture that maintains a small core CSI dataset from which the channel charts are learned. Curation of the core CSI dataset is achieved using a min-maxsimilarity criterion. Numerical validation with measured CSI data demonstrates that our method approaches the accuracy obtained from the complete CSI dataset while using only a fraction of CSI storage and avoiding catastrophic forgetting of old CSI data.

We also applied CC for Ultra-Reliable Low-Latency Communications (URLLC) since it relies on accurate knowledge of channel statistics. Exploiting the spatial consistency of channel statistics arises as a promising solution, allowing a base station to predict the propagation conditions and select the communication parameters for a new user from samples collected from previous users of the network. Based on this idea, [**kallehauge:hal-04102867**] provides a timely framework to exploit long-range channel spatial correlation through so-called statistical radio maps, enabling URLLC communications with given statistical guarantees. The framework is exemplified by predicting the channel capacity distribution both in a location-based radio map and in a latent space rendered by a channel chart, the latter being a localization-free approach based on channel state information. It is also shown how to use the maps to select the transmission rate in a new location that achieves a target level of reliability.

8.8 Molecular Communication

Participants: Malcolm Egan.

This research is lead by Malcolm Egan. It cover axes 1 and 4 and the objective is to elaborate an information and communication theory appropriate for molecular communications. A more detailed definition is provided in [**egan:hal-03934017**]: within many chemical and biological systems, both synthetic and natural, communication via chemical messengers is widely viewed as a key feature. Often known as molecular communication, such communication has been a concern in the fields of synthetic biologists, nanotechnologists, communications engineers, and philosophers of science. However, interactions between these fields are currently limited. Nevertheless, the fact that the same basic phenomenon is studied by all of these fields raises the question of whether there are unexploited interdisciplinary synergies. In this paper, we summarize the perspectives of each field on molecular communications, highlight potential synergies, discuss ongoing challenges to exploit these synergies, and present future perspectives for interdisciplinary efforts in this area.

The Transfer of ‘information’ via molecules is a theme that resonates across the realm of nature, underlying collective behavior, homeostasis, and many disorders and diseases, and potentially holding the answers to some of the life’s most profound questions. The prospects of understanding and manipulating this natural modality of communication have attracted a significant research interest from information and communication theorists (ICT) over the past two decades. The aim is to provide novel means of understanding and engineering biological systems. These efforts have produced substantial body of literature that sets the groundwork for bio-inspired, artificial Molecular Communication (MC) systems. This ICT-based perspective has also contributed to the understanding of natural MC, with many of the results from these endeavors being published in tha special issue co-edited by Malcolm Egan [**kuscu:hal-04361229**].

To model biochemical reaction systems with diffusion one can either use stochastic, microscopic reaction-diffusion master equations or deterministic, macroscopic reaction-diffusion system. The connection between these two models is not only theoretically important but also plays an essential role in applications. In [**egan:hal-04361261**], we consider the macroscopic limits of the chemical reaction-diffusion master equation for first-order chemical reaction systems in highly heterogeneous environments. More precisely, the diffusion coefficients as well as the reaction rates are spatially inhomogeneous and the reaction rates may also be discontinuous. By carefully discretizing these heterogeneities within a reaction-diffusion master equation model, we show that in the limit we recover the macroscopic reaction-diffusion system with inhomogeneous diffusion and reaction rates.

In order to fully exploit the potential of molecular communication (MC) for intra-body communication, practically implementable cellular receivers are an important long-term goal. A variety of receiver architectures based on chemical reaction networks (CRNs) and gene-regulatory networks (GRNs) has been introduced in the literature, because cells use these concepts to perform computations in nature. However, practical feasibility is still limited by stochastic fluctuations of chemical reactions and long computation times in GRNs. Therefore, in [**heinlein:hal-04361281**], we propose two receiver designs based on stochastic CRNs, i.e., CRNs that perform computations by exploiting the intrinsic fluctuations of chemical reactions with very low molecule counts. The first CRN builds on a recent result from chemistry that showed how Boltzmann machines (BMs), a commonly used machine learning model, can be implemented with CRNs. While this approach yields a fixed CRN once deployed, our second approach based on a manually designed CRN can be trained with pilot symbols even within the cell and thus adapt to changing channel conditions. We extend the literature by showing that practical robust detectors can achieve close-to-MAP performance even without explicit channel knowledge.

9 Bilateral contracts and grants with industry

9.1 Bilateral contracts with industry

Participants: Naveed Ahmad, Lelio Chetot, Malcolm Egan, Jean-Marie Gorce, Alix Jeannerot.

We have currently the following partnerships

1. Inria-Nokia Bell Labs common lab : Jean-Marie Gorce lead the future challenge LEarnNet starting on January, 1st, 2024. Alix Jeannerot is also partly funded in the framework of this common lab.

2. The SPIE-ICS / Insa Lyon chaire on IoT has been setup in 2017 by Jean-Marie Gorce for the benefit of the CITIlab. He was the head of this chair from 2016 to 2019, transfered to Frédéric Le Mouel in sept 2019. The remaining budget for Maracas corresponds to one postdoc ended in 2022 (Naveed Ahmad). The work has been published in 2023 [**ahmad:hal-04361063**, **ahmad:hal-04361059**].

9.2 Bilateral grants with industry

Participants: Jean-Marie Gorce, Shashwat Mitra, Fabrice Dupuy, Shashwat Mishra, Claire Goursaud, Guillaume Villemaud, Shanglin Yang.

1. CIFRE with Nokia Bell Labs (2021-2024) on IA For resource allocation in IoT networks. This work is adressed by Mr Shashwat Mishra (PhD student), to be defended in 2024 [**mishra:hal-04360320**].

2. CIFRE with Orange Labs (2022-2025) on passive TAG aided localization with zero-energy-devices anchors. This work is adressed by Mr Shanglin Yang (PhD student), to be defended in 2025.

3. CIFRE Orange Labs (2022-2025) on quantum algorithms for networks. This project is developed in the PhD of Fabrice Dupuy [**dupuy:hal-04244891**].

10 Partnerships and cooperations

10.1 International initiatives

10.1.1 Inria associate team not involved in an IIL or an international program

The Associated team **Federated Automated Deep Learning (FedAutomDL)** lead by Malcolm Egan is with Bapi Chatterjee Assistant Professor, Indraprastha a Institute of Information Technology Delhi. The focus of FedAutoMoDL is to design algorithms, develop convergence theory for federated optimization of both the architecture and weights in DNNs, and study applications in the Internet of Things (IoT). This is going to be achieved by complementary interactions between Inria and IIIT-Delhi. Expertise in distributed computing will be provided by IIIT-Delhi, which currently focuses on scalable machine learning, neural architecture search, and distributed optimization. Expertise in probabilistic analysis of algorithms as well as the IoT will be provided by the Inria team, which has a strong background in information theory, statistical signal processing and applications in the IoT, including both theoretical and experimental aspects

10.2 International research visitors

10.2.1 Visits of international scientists

Incoming visitors :

- 24 January 2023, Prof. Eleftherios Kofidis (University of Patras, Greece). Discussions on tensor algorithms in wireless communications.

- 20 April 2023, Dr. Khac-Hoang Ngo (Chalmers University, Sweden). Discussions on multiple-access methods and federated learning.

- 22 May-2 June 2023 Bapi Chatterjee, May. In EA FedAutoMoDL, gave a seminar on distributed stochastic optimization for machine learning.

10.2.2 Visits to international teams

Outgoing visits :

- Maxime Guillaud: 3-6/05/2023, Vellore Institute of Technology (India), visited the School of Electronics Engineering.

- Malcolm Egan: 20-25/11/2023, visted IIIT-Delhi, Delhi, India.

10.3 European initiatives

10.3.1 Horizon Europe

INSTINCT The project INSTINCT (Joint Sensing and Communications for Future Interactive, Immersive, and Intelligent Connectivity Beyond Communications) is one of the projects selected in the SNS-6GIA program in the track "Wireless Communication Technologies and Signal Processing". INRIA (MARACAS and DYOGENE teams) will participate to the project that will start on January, 1st, 2024.

Participants: François Baccelli, Leonard Cardoso, Jean-Marie Gorce, Maxime Guillaud, Cyrille Morin.

10.3.2 H2020 projects

WINDMILL The project WINDMILL (Machine Learning for Wireless Communications)received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 813999.

Participants: Mateus Pontes Mota, Jean-Marie Gorce.

WINDMILL project

Title: Machine Learning for Wireless Communications

Duration: From January 2020 to December 2023

Partners:

- Aalborg Universitet
- EURECOM, Sophia Antipolis
- CTTC, Spain
- Aalto University, Finland
- Universita Degli Studi di Padova
- World Sensing
- Nokia Bell Labs
- Ericsson
- SDSC
- BOSH
- Centrale Supelec, France
- Cornell University
- Insa Lyon, France
- Deepsig
- Intel
- Mitsubishi Electric
- Telenor
- Universitat polytechnica di Catalunya
- University of Stuttgart
- The University of Texas, Austin, USA

- Virginia Tech, USA

Inria contact: Jean-Marie Gorce

Coordinator: Cedomir Stefanovic

Summary: As wireless communication networks evolve towards 5G and beyond, we are entering an era of massive connectivity, massive data, and extreme service demands. However, it is challenging to handle such complexity and data volume successfully. A promising approach to this issue is to develop new network management and optimization tools based on machine learning. This presents a major shift in the design and operation of wireless networks. At the same time, the approach demands a new type of expertise: a combination of engineering, mathematics and computer science disciplines. The ITN project WindMill addresses this issue by providing relevant interdisciplinary training. In the course of the project, 16 Early Stage Researchers (ESRs) will be trained in integrating wireless communications and machine learning. The trainings will be provided by a consortium of leading international research institutes and companies with experts in wireless communications and machine learning. In this way, project will also nurture the sense of responsibility of the ESRs and the other participants through personal engagement in the training program and by promoting teamwork through collaborative joint projects.

TESTBED2

Participants: Samir Perlaza.

TESTBED2 project on cordis.europa.eu

Title: Testing and Evaluating Sophisticated information and communication Technologies for enaBling scalablE smart griD Deployment

Duration: From February 1, 2020 to July 31, 2025

Partners:

- INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET AUTOMATIQUE (INRIA), France
- INSTITUTE OF ELECTRICAL ENGINEERING CHINESE ACADEMY OF SCIENCES (IEECAS), China
- JINAN UNIVERSITY (JNU), China
- UNIVERSITY OF NEBRASKA (UN), United States
- UNIVERSITY OF DURHAM (UNIVERSITY OF DURHAM), United Kingdom
- BEIA CONSULT INTERNATIONAL SRL (BEIA), Romania
- DOTX CONTROL SOLUTIONS BV (DOTX CONTROL SOLUTIONS), Netherlands
- UNIVERSITY OF NORTHUMBRIA AT NEWCASTLE (Northumbria University), United Kingdom
- TRUSTEES OF PRINCETON UNIVERSITY (PRINCETON), United States
- ORGANISMOS TILEPIKOINONION TIS ELLADOS OTE AE (HELLENIC TELECOMMUNICATIONS ORGANIZATION SA), Greece
- HERIOT-WATT UNIVERSITY (HWU), United Kingdom
- CHINA ELECTRIC POWER RESEARCH INSTITUTE (SEAL) SOE (CEPRI), China
- DEPSYS SA (DEPSYS), Switzerland
- THE REGENTS OF THE UNIVERSITY OF CALIFORNIA (LOS ANGELES UCLA SANTA BARBARA UCSB DAVIS UCD RIVERSIDE UCR SAN DIEGO UCSD SANTA CRUZ UCSC IRVIN), United States

- UNIVERSITAET KLAGENFURT (UNI-KLU), Austria
- EBERHARD KARLS UNIVERSITAET TUEBINGEN (UT), Germany
- SOUTHEAST UNIVERSITY, China
- STICHTING NEDERLANDSE WETENSCHAPPELIJK ONDERZOEK INSTITUTEN (NWO-I), Netherlands

Inria contact: Samir PERLAZA

Coordinator:

Summary: Smart grids represent an electricity network that can intelligently integrate generators, consumers and energy storage in order to efficiently deliver electricity. There is a clear consensus that smart grids can provide many innovative services – to date the EC has devoted €360,413 million to support 527 projects on developing smart grid services. Decision-making plays a vital role in these services. But the computational complexity of decision-makings could grow explosively with the size of smart grid infrastructure, the number of devices/users, or the amount of data; If this scalability issue was underestimated, smart grid services can end up with poor performance or limited function, making these services impractical to meet the needs of real-life or industrial-scale deployment. Hence, there is an urgent need to solve the research problem: to what extent the performance and function of smart grids can be maintained without having significant increase of the computational complexity when its scale is changed in terms of smart grid infrastructure size or the number of devices/users? TESTBED2 is a major interdisciplinary project that combines wisdoms in three academic disciplines - Electronic & Electrical Engineering, Computing Sciences and Macroeconomics, to address the aforesaid problem. The main focus is on developing new techniques to improve the scalability of smart grid services, particularly considering the joint evolution of decarbonised power, heat and transport systems. Moreover, new experimental testbeds will be created to evaluate scalable smart grid solutions. Overall, the main objective of this project is to coordinate the action of 13 Universities (7 in EU, 3 in US, and 3 in China) and 5 enterprises (3 SMEs and 2 large enterprises) with complementary expertise to develop and test various promising strategies for ensuring the scalability of smart grid services, thereby facilitating successful deployment and full roll-out of smart grid technologies.

10.3.3 Other european programs/initiatives

CHASER - CHIST-ERA program

Participants: Maxime Guillaud, Yamil Vindas Yassine.

CHASER project

Title: Channel Charting as a Service

Duration: From November 1, 2023 to October 31, 2026

Partners:

- Institut für Integrierte Systeme ETH Zürich
- Aalto University, Finland
- Inria, France
- Dept. of Polymer Engineering University of Minho, Portugal

Inria contact: Maxime Guillaud

Coordinator: Christoph Studer (Institut für Integrierte Systeme ETH Zürich), Switzerland

Summary: Channel charting (CC) is an emerging application of self-supervised machine learning (ML) to wireless communication which leverages the fact that wireless communications systems continuously collect data about the electromagnetic propagation channel. This data, known as channel state information (CSI), is high-dimensional and acquired at fast rates but typically discarded immediately after use. In contrast, CC recycles acquired CSI data by means of dimensionality reduction (DR) to learn a so-called channel chart. This channel chart is essentially a low-dimensional representation of the CSI with the salient property that users who are close in the channel chart are also close in physical space. Put simply: CC is a method that produces a pseudo-location with no recourse to classical positioning methods, potentially opening up a range of location-based applications to operate with significantly reduced overhead. Real-world experiments in single base-station scenarios have demonstrated the practical viability of CC. Despite these encouraging preliminary results, it is unclear whether CC can generate pseudo-location information at the radio access network (RAN) scale (e.g., for multiple base stations) with sufficient quality to replace true location information for certain location-based services and applications. The objective of this project is to develop methods and algorithms allowing to implement network-wide CC, develop its predictive capabilities when applied to real-world use cases with heterogeneous users and dynamically changing environments in which CSI may be affected by changes in the electromagnetic propagation environment. With the ultimate goals of developing CC into a robust and versatile pseudo-positioning method and of enhancing the expressivity of the channel chart beyond merely replacing location information to serve as a general basis for context-based services, we envision channel charting as a service (CaaS), which assists a number of network functions and user-level applications with a CC-based pseudo-location management architecture accessible through a dedicated application programming interface. To achieve these goals, we will perform fundamental research on the algorithm and implementation levels, validate our solutions by gathering long-term CSI measurements in dynamically changing environments, and optimize CaaS for radio resource management (RRM) in RAN. The project will lift CC from technology readiness level (TRL) 3 to TRL 4.The expected impacts of the CHASER project lie in providing ML-based predictive RRM to enhance the efficiency, reliability, and latency of wireless communication. In particular, predictive handover and MIMO beamforming management will be performed. Furthermore, the project will consider new context-aware applications around which we will develop a set of representative benchmarks consisting of use cases, reference algorithm implementations, and CSI datasets enabling benchmarking of CC algorithms in a reproducible manner. We will also develop novel evaluation strategies for predictive tasks that rely on self-supervised ML methods in wireless systems. The cross-disciplinary research of CHASER will enhance long-term interaction between the machine learning, wireless communications, real-time, and distributed computing communities. We shall expand classical DR towards more realistic non-stationary observation models, provide solutions to distributed manifold alignment problems, and implement real-time dataset distillation. Thus, beyond its immediate impacts on the field of wireless communications, our research has the potential to significantly advance the versatility of the ML and DR toolbox, and will strengthen the links with the real-time computing community.

10.4 National initiatives

10.4.1 ANR

- ANR U-Wake *Ultra-Low Power Wake-up Radio* (2020-2024, 150 keuros, leader : IETR Lille) : The scientific motivation of U-Wake is to achieve a fully self-powered wake-up receiver prototype. This is made possible through the adjunction of ultra-low powerelectronic subparts (RF demodulator, neuro-inspired detector and SNN) and RF energy harvesting. Moreover, this object will be realized in standard industrial CMOS technology to allow low cost andwide scale deployment. The project supports the PhD of Guillaume Marthe.

10.4.2 BPI France

- BPI – France Relance – 5G Events Labs [Consortium: CEA – Centre de Saclay, Ericsson, Inria, Orange] [2021–24]. The 5G Events Labs project aims to boost the economic activity of the events, culture and sports sectors, around ten major sites in France where Orange and its partners will offer 5G coverage, technological platforms and adapted support enabling companies to leverage these technologies and incubate innovations in the areas of services for attendees and organizers. Maracas contributes in grant-free access solutions for IoT, in collaborative and decentralized estimation algorithms.

10.4.3 PEPR - Network of the Future

Networks of the future represent a key issue for French and European industry, society and digital sovereignty. This is why the French government has decided to launch a dedicated national strategy. One of this strategy's priority ambitions is to produce significant public research efforts so the national scientific community contributes fully to making progress that clearly responds to the challenges of 5G and the networks of the future. In this context, the CNRS, the CEA and the Institut Mines-Télécom (IMT) are co-leading the '5G' acceleration PEPR to support upstream research into the development of advanced technologies for 5G and the networks of the future. Inria is involved into 8 research projects over the 10 supported by the program, with the participation of 11 teams of the theme "Networks and Telecommunications" and the coordination of the PC9-Founds.

MARACAS participates to the following projects :

- MARACAS, with TRIBE, contributes to PERSEUS. PERSEUS focuses on the technologies, processing and optimization of cell-free massive MIMO (CF-mMIMO) networks in the sub-7 GHz frequency band. CF-mMIMO technology, combined with reconfigurable intelligent surface (RIS) techniques and artificial intelligence (AI) tools, is a highly promising solution for beyond-5G networks. PERSEUS aims to increase the maturity of these technologies in order to achieve power- and spectrum-efficient massive access. The project covers several aspects with a view to designing a "cell-free massive MIMO" network: (i) design, manufacture and test of RF circuits, RIS and antennas, (ii) proposal of robust PHY and MAC layers based on signal propagation measurements and the incorporation of hardware imperfection models, and (iii) development of proofs of concept to practically evaluate the performance of the selected algorithms and the hardware manufactured within the framework of the project.

- MARACAS, with DYOGENE and NEO, contributes to FOUNDS. The project organizes fundamental research in the following directions:

  - The study of the fundamental theoretical limits in the sense of physics and information theory, with many open questions linked to the use of the spatial dimension, strong latency constraints or even the taking into account of the signification of what is transmitted from coding, protocols and up to the physical layer.

  - The determination of the optimal spatial organization of the network elements, taking into account the limitations of information theory. This will require new mathematical tools and models, which will be key elements of this project.

  - The design of real-time and non-real-time distributed control algorithms to exploit such network architectures. The main objective here is to get closer to the fundamental limits studied in this project.

- MARACAS (with DIANA) contributes to the PC Plateforms, which includes the development and the integration of CorteXlab into SLICES-FR. SLICES-FR is the French node of the European initiative SLICES, a flexible platform designed to support large-scale, experimental research focused on networking protocols, radio technologies, services, data collection, parallel and distributed computing and in particular cloud and edge-based computing architectures and services.

11 Dissemination

11.1 Promoting scientific activities

11.1.1 Scientific events: organisation

General chair, scientific chair Maxime Guillaud was TPC co-chair of the 6G Wireless Foundations Forum, Sophia-Antipolis, July 10-11, 2023.

Jean-Marie Gorce co-organized with François Baccelli the Workshop on "Performance Guarantees in Wireless Networks", March 2023, IMT Paris.

Member of the organizing committees Malcolm Egan co-organized:

- GDR ISIS workshop on Goal-Oriented and Semantic Communications, 10/11/2023, Inria Paris.
- Workshop on Molecular Communication Approaches for Wetware Artificial Life in the ALIFE2023 Conference, Hokkaido, Japan (Hybrid), July 2023.

11.1.2 Scientific events: selection

Member of the conference program committees Jean-Marie Gorce is

- a member of the Technical Program Committee of the GRETSI conference (Sept 2023, Grenoble).

Malcolm Egan is

- TPC GLOBECOM 2023
- TPC ICC 2023/2024

Leonardo Cardoso is

- a member of the Technical Program Committee of the ICC conference (June 2024, Denver, CO).
- a member of the Technical Program Committee of the WCNC conference (April 2024, Dubai, UAE).
- a member of the Technical Program Committee of the ICMLCN conference (May 2024, Stockholm, Sweden).

Member of the editorial boards Maxime Guillaud is an associate editor of the IEEE Transactions on Wireless Communications since 2019

Claire Goursaud is an associate editor of Transactions on Emerging Telecommunications Technologies since 2016

Claire Goursaud is an associate editor of Internet Technology Letters since 2017

Malcolm Egan is a guest editor of IEEE Transactions on Molecular, Biological and Multi-Scale Communications in 2023.

11.1.3 Invited talks

Maxime Guillaud is a Distinguished Lecturer of the IEEE Communications Society for the period 2023-2024.

Maxime Guillaud gave the following invited talks:

- invited talk at the Workshop on Performance Guarantees in Wireless Networks, LINCS, March 8-9, 2023
- invited talk in the IEEE Communication Theory Technical Committee "2+1" Online Event – March 10, 2023
- invited talk on Wireless Channel Charting at EURECOM, March 30, 2023

- keynote talk at the ViTECoN Conference, Vellore, India, May 5, 2023
- invited seminar at the London Symposium on Information Theory May 24, 2023
- invited talk at the IEEE Communications Theory Workshop, Hualien, July 4, 2023
- invited talk at the International Symposium on Topics in Coding Brest, September 6, 2023

Jean-Marie Gorce gave the following invited talks:

- invited talk at the Zugspitze workshop on Communications, 23-26 June 2023.
- invited talk on at the Workshop on “Performance Guarantees in Wireless Networks”, March 2023, IMT Paris
- invited talk (visio) at Centrale/Supélec for the group of Marco Di Renzo.

Malcolm Egan gave the following invited talks:

- Computer Science Department, IIIT-Delhi, India, Nov. 2023.
- ICI group in ETIS, ENSEA, July 2023.

11.1.4 Leadership within the scientific community

Maxime Guillaud is

- a member of the Steering Committee of CNRS GdR ISIS (Information, Signal, Image & ViSion)
- a member of the "Signal Processing for Communications and Networking" Special Area Team of EURASIP

11.1.5 Scientific expertise

Jean-Marie Gorce was

- Member of the evaluation comittee of Inria.
- Member of the recruiting committee for a professor position at CERGY-ETIS.
- Representative of Inria in the preparation of the PEPR-NF (Network of the Future).

11.1.6 Research administration

Jean-Marie Gorce was

- Head of Science for the Inria Lyon Centre.
- Member of the Evaluation Committee of Inria.
- In charge of the PEPR-NF preparation, for Inria, member of the PEPR-NF operational committee.

Malcolm Egan was

- Member council of the CITI Laboratory
- Lyon representative for the Inria Mission Jeunes Chercheurs
- Member COMI Lyon
- Organizer seminar of the CITI Laboratory

11.2 Teaching - Supervision - Juries

11.2.1 Teaching

Maracas members are teaching regularly at the telecommunications department of INSA Lyon. We deliver courses with strong connections with our research activity. The main ones are:

- Bachelor : L Cardoso - Electromagnetism and Wave Physics, 104 eqTD, L2, First Cycle Dept, INSA Lyon, France.
- Bachelor : L Cardoso - Mathematics for Engineering, 60h eqTD, L1, First Cycle Dept, INSA Lyon, France.
- Bachelor : L Cardoso, C Goursaud, J. Hamié - Digital Communications, 80h eqTD, L3, Telecommunications dept, INSA Lyon, France.
- Bachelor : L Cardoso, C Goursaud, Research projetcs - 32h eqTD, L3, Telecommunications dept, INSA Lyon, France.
- Master : JM Gorce, L Chetot - Advanced Digital Communications, M1, Telecommunications dept, INSA Lyon, France.
- Master : JM Gorce, L Chetot - Radio Access Networks, 32h eqTD, M1, Telecommunications dept, INSA Lyon, France.
- Master : C Goursaud - Communications Systems, 32h eqTD, M1, Telecommunications dept, INSA Lyon, France.

11.2.2 Supervision

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Jean-Marie Gorce supervised the PhD of Mateus Pontes Mota (started on Oct, 2020. defense planed for 23, January, 2024).

Jean-Marie Gorce supervised the PhD of Shashwat Mishra (started on Oct, 2021. defense planed for September 2024).

Jean-Marie Gorce co-supervise with Guillaume Villemaud the PhD of Shanglin Yang (started on Oct 2022, defense planed for September 2025).

Jean-Marie Gorce andMalcolm Egan supervise the PhD of Alix Jeannerot (started on Oct 2021, defense planed for September 2024).

Claire Goursaud supervised the PhD of Idham HABIBIE (started on Oct 2020, defense done on December 2023).

Claire Goursaud supervised the PhD of Guillaume MARTHE (started on Oct 2021, defense planed for December 2024).

Claire Goursaud supervised the PhD of Fabrice DUPUY (started on Jan 2021, cancelled due to health issues).

Claire Goursaud supervised the PhD of Romain PIRON (started on Nov 2023, defense planed for December 2026).

11.2.3 Juries

- Jean-Marie Gorce was:
  - Reviewer of the PhD of Ngoc Lam Dinh, CEA Leti, et Université UGA, March 2023. "Orchestration centralisée et gestion des ressources hybrides pour les communications ultra-fiable et à faible latence (URLLC)".

  - Reviewer of the PhD of Pierre Popineau,ENS Paris et Université Paris Sciences et Lettres, June 2023. "Etude de la dynamique de processus ponctuels spatiaux appliqués aux réseaux de communication sans fil".
  - Chair of the PhD jury for Yibo Quan, Institut Polytechnique de Paris, July 2023. "Performance evaluation and resource allocation in millimeter waves device-to-device networks with beamforming".
  - Chair of the PhD jury for Nicolas Charpenay, INRIA Rennes, Nov 2023. "Théorie de l'information zéro-erreur dans les réseaux : graphes, codage pour le calcul de fonctions et dualité source-canal".
  - Chair of the PhD jury for Paul Fermé, ENS Lyon, Nov 2023. "Approximation Algorithms for Channel Coding and Non-Signaling Correlations".
  - Reviewer of the HdR of Camille Leroux, Université de Bordeaux, June 2023. "Adéquation Algorithme Architecture pour le Codage de Canal"
  - Reviewer of the HdR of Bertrand Le Gal, Université de Bordeaux, Fev 2023. "Adéquation algorithme architecture – approches matérielles et logicielles pour les applications de communications". numériques
  - Reviewer of the HdR of Elsa Dupraz, IMT Bretagne, Oct 2023. "Vers de nouvelles applications du codage canal".

- Maxime Guillaud was:
  - Member of the PhD committee of Aymen Ktari, Telecom Paris, December 2023, "Machine Learning for beam Alignment in mmWave massive MIMO."
  - Reviewer of the PhD thesis of Hamza Djelouat, University of Oulu, Finland, "Optimizing Massive Random Access: Leveraging Correlation Models and Sparse Recovery Algorithms.

- Claire Goursaud was:
  - Reviewer of the PhD of Joseph DOUMIT, IMT Atlantique, December 2023. "Optimisation de l'allocation des ressources pour l'internet des objets avec un accès non coordonné et non orthogonal au spectre".
  - Reviewer of the PhD of Camille MONIERE,Université Bretagne Sud, January 2023. "Implémentation Temps-Réel d'un Récepteur Quasi Cyclic Short Packet.".
  - Member of the PhD committee of Francois VERDEIL, Telecom Paris, December 2023, "Machine Learning for beam Alignment in mmWave massive MIMO."
  - Member of the PhD committee of Aymen Ktari, Telecom Paris, December 2023, "Machine Learning for beam Alignment in mmWave massive MIMO."

11.3 Popularization

11.3.1 Internal or external Inria responsibilities

Maxime Guillaud is a member of the "Mobile Communication Networks" expert committee of ARCEP, the French telecommunications regulatory authority

12 Scientific production

12.1 Publications of the year