RESEARCH CENTRE

Grenoble - Rhône-Alpes

IN PARTNERSHIP WITH:

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2021

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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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This new paradigm makes the aforementioned classical network architecture based on a centralized approach out-of-date.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. [56, 54, 61].

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 [19] 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 1 represents the most important performance criteria to be considered to achieve reliable communications. These metrics fit with those considered in 5G and beyond technologies [58].

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 1). However, the other constraints can be efficiently introduced by using a non-asymptotic formulation of the fundamental limits [57, 59] 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

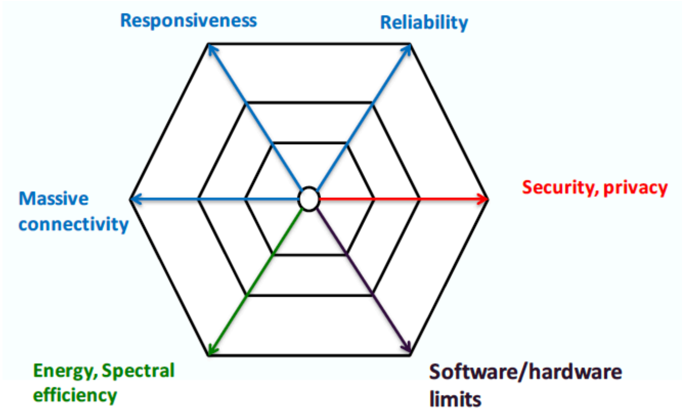

Figure 1: Main metrics for future networks (5G and beyond)

statistical signal processing, control theory, and game theory. Wireless networks is the emblematic 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 [8] of for multi-constrained systems [18].

  This also means revisiting the fundamental estimation-detection problem [60] 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* [53] 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*.

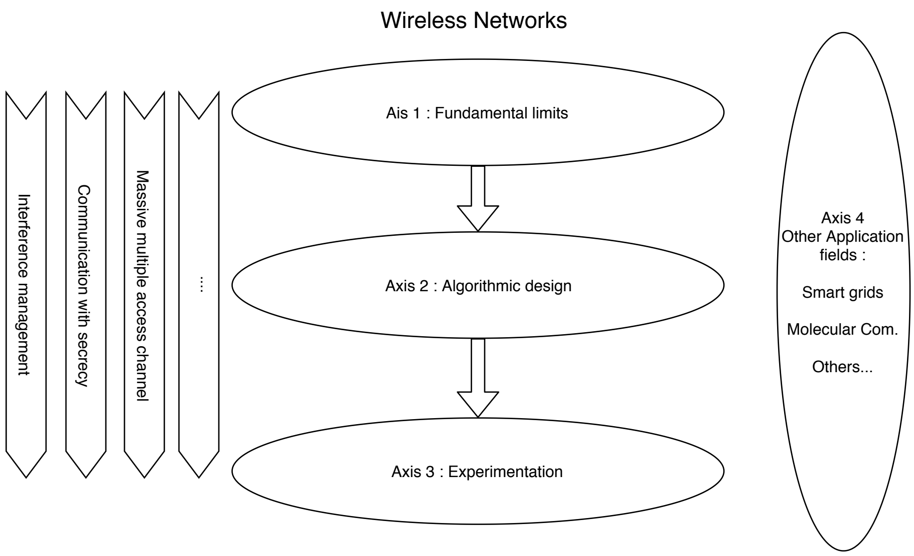

Figure 2: Maracas organization

- **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 [62, 55].

  Another emerging research direction relies on using machine learning techniques [52] 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 [1, 10]. 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 [11] and the original paradigm of molecular communications [6].

  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

Dadja Anade, Hassan Kallam and Cyrille Morin successfully defended their PhD.

We explored new side-road studies in axis 4.

The cooperation with Nokia Bell Labs is strengthen with one more PhD starting.

We achieved new results around molecular communications.

7 New software and platforms

We evaluate different algorithmic solutions in multi-user communication scenarios in GNUradio and we propose standard implementations on CorteXlab. Both contributions are discussed in the following sections.

7.1 New software

7.1.1 cortexlab-fftweb

Keywords: Experimentation, Data visualization, SDR (Software Defined Radio)

Functional Description: fftweb is a real-time spectral (FFT) visualization of one or several signal, embedded in a web page. The FFT is computed in a GNURadio block, then sent to a gateway server, which serves the web page, associated javascripts, and signal websockets. The end user only has to use the GNURadio block and and the web page, and doesn't need to bother about the internal details of the system. fftweb has been developped specially for the CorteXlab testbed but with minor adaptations, it can be used in other contexts, and also can be used to draw more generic real-time graphs, not only FFTs. Technologies: GNURadio, python, python-gevent, Javascript, D3JS

Contact: Matthieu Imbert

7.1.2 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

7.1.3 cortexlab-webapp

Keywords: Experimentation, SDR (Software Defined Radio)

Functional Description: User management module, 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

Contact: Pascal Girard

Partner: Insa de Lyon

7.1.4 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

7.2 New platforms

Participants: Paul Estève, Pascal Girard, Jean-Marie Gorce, Mathieu Imbert, Cyrille Morin, Amaury Paris, Mateus Pontes Mota, Léonardo Sampaio Cardoso.

Figure 3: FIT/CorteXlab facility

7.2.1 FIT/CorteXlab

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 spite of the global Covid pandemic, the years of 2020 and 2021 have seen several key developments in CorteXlab:

- Faradization repairs in the experimentation room due to a flood in 2018. This required a service interruption of about 2 months with a partial disassembling of the experimentation room and re-assembling. The room is now fully operational and back in (before flood) working order.
- The establishment of a new and complementary experimentation paradigm based on Docker virtualization and direct access to nodes. While its development started in 2019, final developments made it more usable allowing it to enter mainstream, as of 2020. This new experimentation paradigm allows for more control on the part of the user than ever before, while retaining the level of security and manageability expected from the general usage of such a kind of platform. This development also allows for more flexible experiments, easing the use of non GNU Radio experiments with other kinds of SDR frameworks, like for example, OpenAir Interface. Eventually, the old Minus-based experimentation system will be seamlessly migrated into hidden Docker style experiment. This new experimentation paradigm has been the focus of a tutorial at the GNU Radio Europan Days 2021 and gathered much attention (Gnu radio days).
- The usage of robots in experiments has been further developed with a fully functional turtle bot equipped with LIDAR ranging and mapping and an USRP B210, able to roam the experimentation

room under different and programmable mobility patterns. The usage of robot based experiments have also started with the Deep Learning Based Transmitter Identification works of Cyrille Morin [47] et al. The robot usage will be integrated into the experimental software tools to automate the launching and stopping of the robot for each experiment.

- The web user interface was greatly developed during 2020 (went into production January 2021) as the first web interface elements of several to come to help ease the usage of CorteXlab and lower the entry ticket to the platform. This web interface allows for users to manage their own accounts, freeing engineer time to other more important developmental tasks, as well as increasing the security to social hacker attacks.

- Repair of the remotelly controlled Electric Power Switches (EPS). The EPSs are essential elements of the CorteXlab platform as it allows for remote control of the nodes' computers as well as maintenance. Many EPSs have experienced failure in the years since CorteXlab's inauguration. This hindered the full usage of the testbed. They have been fixed by the platform engineers and have had their life-time extended. However, a more realiable solution for electrically controlling the nodes must be sought.

- A reservation tool has seen its development start in 2021 and shall go on production early 2022. It will allow fast and easy reservations of the CorteXlab resources, which will potentially increase the pool of potential CorteXlab users, as well as free engineer more time. Experiment monitoring tool and service aggregation portal are next functionalities to be developped in 2022.

- As the radio hardware in the CorteXlab experimentation room gets old and outdated, its replacement by newer and more capable radios has become an important step to maintain CorteXlab a state of the art platform. As such, the dephasing of the old PicoSDRs have started, with two being replaced by newer USRPs N2944R, which possess dual transceivers that are phase synchronised, sampling at a maximum bandwitdh of 160 MHz. Additionally 3 other new USRPs N2944R have been installed in empty slots raising the total USRPs N2944R to 5. They have been connected to the synchronization network of octoclocks and have become operational as of November 2021. These new USRPs will enable to experiment with demanding 5G systems as well as more refined measurement capabilities due to its high bandwidth. It will be paramount for new Deep Learning based experiments, such as radio localization and identification.

- The develoment of a LoRa basis for experimentation in CorteXlab has also seen the light of day during 2021 (described above as an independent software: Cortexlab_LORA_PHY). A new LoRa starting point for experimenting has been created, based from an existing EPFL implementation, with the adition of dynamic features as well as a simplified MAC layer. This was the work of both an Inria engineer as well as an intern. A deliverable from this project is a tutorial, hosted at the CorteXlab wiki page (tutorial Lora on CorteXlab) and presented in [43].

- In collaboration with Michele Wigger and her group from IMT Paris, with Yasser Fadlallah, we supported the implementation of a polar code based caching technique in CorteXlab [28]. A complete implementation of a polar code based caching has been proposed and evaluated. A tutorial will be made available soon on CorteXlab page.

- In the WindMill European project and in the framework of the PhD of Mateus Pontes Mota, we are extending the IoT framework (soft CorteXlab-IoT Framework) to support the concept of emerging protocols, Mateus is targeting in his PhD thesis co-supervised with Alvaro Valcarce from Nokia Bell Labs. The objective is to experiment and to show that a subset of nodes can learn a signaling protocol.

In the coming years, we will pursue the following objectives for CorteXlab:

1. Continued update of old and rarely used radio hardware and replace it with new, more useful, and updated hardware. While the USRPs N2932 are still good options for many kinds of experiments, they present certain limitations with respect to frequency ranges, bandwidth and communication speeds with the computer interface, meaning that they are becoming less and less relevant as time

passes. The PicoSDRs have not presented a great usage profile since they are hard to use, in either pure GNU Radio mode as well as FPGA mode. They demand a great investment of tools and time from the user side and are less well documented and supported by the manufacturer. The ideal scenario would be to replace all PicoSDRs with dual transceiver USRPs N2944R and co-equip all USRP N2932 nodes with dual channel N2900 (B210 equivalents) to offer more flexibility to the users and allow for other SDR systems, like Eurecom's Openair Interface, to be easily deployed in CorteXlab.

2. Update all controlling node PCs with new and more capable machines, able to increase the complexity of the GNU Radio chains running in these machines. With the rise in popularity of Deep Learning systems for radio, some of these machines could also be equipped with a GPU unit to aid with in loco — on line Deep Learning systems.

3. Update the support equipment, increasing the networking bandwidth between the nodes themselves and also the server, which would allow for more relevant distributed (auto-coordination, distributed learning, etc...) and/or centralized (Deep Learning aggregation, cloud RAN, etc...) techniques to be studied.

4. The massive multi-user scenarios, one of the main targets of CorteXlab, are still a challenging problem do deal with both from the theoretical and experimentation fronts. We aim at providing several tools to ease with the experimentation of such scenarios, such as a) ready-made, usable multi-user frameworks with pluggable parts that allow for fast experimentation; b) extensive datasets as well as the tools used to create them, for users working with Deep Learning; c) more realistic (and close to standard compliance) physical layer systems, that will either be created from scratch or adapted from open source systems, will allow users to get closer to real life systems while remaining in the stable environment of CorteXlab's experimentation room.

5. Nodes outside the experimentation room for real-life, real interference profile communications tests in the ISM band (and other bands we might be able to get licensing deals), under regulated norms. This objective requires tests to restrain the nodes' transmission frequencies and powers to the ones allowed as to avoid harmful interference to other systems.

We proposed the use of CorteXlab in the framework of the PEPR 5G and we expect to collaborate in the future SNS-IA program of Horizon Europe. More specifically, CorteXlab can be used to explore machine learning based radio, resource management and also tu evaluate joint sensing and communication concepts for twinning worlds.

8 New results

In 2021, as for all of us, many collaborative projects have been delayed due to the pandemia, conferences held remotely, and many experimental activites have been postponed. For instance, the implementation of our two PhC European fundings, one with Serbia and the other with Austria have been delayed.

Let us first give a global overview of our research results, along three main lines : fundamental results, multi-user network scenarios and cross-roads exploration.

Fundamental results: Many applied problems in communication can be evaluated under the light of applied probabilities, at the root of information theory and estimation theory. A part of our work in axis 1 contributes in this area. In 2021 we obtained three important results

- The mutual information between input and output variables in a network channel relies on the computation of the cumulative distribution function of a sum of random variables. We proposed new bounds based on the saddle-point approximation [33, 45, 48].

- Evaluating dependence between random variables is an important problem in general with many applications in communications. We explored how extreme values for regularly varying models can be used for dependence testing [35].

- Deep learning is becoming a fundamental brick in networks. With the objective of improving learning in deep neural networks, we studied asynchronous optimization methods for efficient training of Deep Neural Networks [39].

Multi-user network scenarios : Multi-user network scenarios constitute the natural playground for our research, for instance considering an isolated cell in the downlink, or a LORA rando access topology, etc... For each scenario, we explore it under three perspectives: fundamental limits (axis 1), efficient algorithms (axis 2) and experimental evaluation (axis 3). Before going deeper in these contributions, we herein summarize the scenario studied this year

- **Point-to-point transmission**: despite its long history and well-established results, the basic scenario made of one transmitter and one receiver still represents challenges: Typically, to adapt the transmission to new propagation channels (e.g. THz, VLC) with non classical properties, but also to support new QoS requirements (URLLC), which occurs especially in the context of machine to machine communications. Last but not least, revisiting the P2P communication problem under the light of machine learning may bring new breakthrough in terms of encoder/decoder complexity and adaptability.
  Our contributions this year concern first the evaluation of the capacity for a channel with additive multivariate α-stable noise [27]. We also studied the second-order capacity of multi-delay constrained transmission of short packets [41, 51] (axis 1). Lastly, in collaboration wih Jakob Hoydis and Fayçal Aoudia (Nokia), we elaborated deep learning strategies [36, 49, 47] (axis 2) at the PHY layer.

- **Multiple access channel**: in this setup, individual nodes randomly send packets to a unique BS. In the IoT context, one isolated cell may serve thousand of nodes with low transmission probability. The design of an optimal setting for such scenario requires to consider as a whole the PHY and the MAC layers either in the downlink or the uplink. In this area we finalized the derivation of a fundamental limit with Philippe Mary (INSA Rennes) and Jean-Marc Kélif (Orange) in [29] (axis 1). In axis 2, we also proposed the first studies considering correlated sources for active nodes detection [23] and resource optimization. In collaboration with Petar Popowski and Anders Kalør (Aalborg U) and Laurent Clavier (IMT Lille), we proposed a stochastic approach for resource allocation [32, 44]. For the same scenario, with a signaling channel, we explored the use of reinforcement learning to build an approach allowing mobiles and BS to learn by themselves the signaling protocol [50]. From an experimental perspective (axis 3), we also build a new software (Cortexlab_LORA_PHY) to allow the evaluation of Lora technology [43].

- **MU-MIMO in the uplink**: In this scenario several mobile nodes communicate with a base station equipped with multiple antennas. The transmitters are known and synchronized. We proposed different strategies relying on deep learning [30, 34, 37] (axis 2), in collaboration with Nokia (Jakob Hoydis, Fayçal Aoudia) or with CTTC (Carles Anton, Xavier Mestre).

- **Interference network**: in such a configuration multiple transmitters and receivers try to transmit simultaneously with no or a few coordination. We conducted an experimental evaluation of interference statistics [24] with Laurent Clavier (IMT Lille) Troels Pedersen and Ignacio Rodriguez (Alborg U) and Mads Lauridsen (Nokia), showing the distribution of the interference power is heavy tailed. We also designed an optimal receiver for this impulsive noise in collaboration with all partners froml ARburst project (INSA Lyon and IMT Lille) [40]. In the PhD of Hassan Kallam [46], we also proposed a new topological interference management (TIM) construction which more efficiently deals with the non-asymptotic SNR regime (axis 1).

- **Cellular network**: The cellular model corresponds to a setup with multiple BS and multiple mobiles in each cell, with intereference between adjacent cells. Homa Nickbakht explored the capacity of this scenario with Mixed delay traffic in Wyner's symmetric network (axis 1) in the continuation of her PhD, with Michele Wigger and Shlomo Shamai [42].

- **Single server multi-user network :** In this work, we consider a unique BS having to transmit files to users upon their request. Users have caching memory and then the objective is to work on coded caching to increase the transmission efficiency [28]. Our contribution (Yasser Fadlallah) was on the experimental evaluation with CorteXlab while the algorithm was proposed by Michele Wigger and Philippe Ciblat (IMT Paris).

Crossroad studies: The objective of axis 4 is either to explore new setups not directly related to the wireless context, or to explore new techniques or models that could be useful for wireless. This year we continued to investigate on :

- Molecular communications: Modeling, capacity and bounds of molecular channels [22, 26, 27].
- Quantum algorithms : We started the investigation on exploiting quantum algorithms to solve complex problem in multi-user communications, especially for the multiple access channel mentioned above [38].
- Online Model Identification and Production Optimization Using Modifier Adaptation [31].

8.1 Axis 1: fundamental limits

8.1.1 Contributions in Applied Probability

Participants: Dadja Anade, Malcolm Egan, Jean-Marie Gorce, Philipe Mary* (INSA Rennes), Samir Perlaza* (Inria, NEO), Vyacheslav Kungurtsev* (Czech Technical U.), Bapi Chatterjee* (IST Austria), Dan Alistarh* (IST Austria).

rational : Most fundamental results in information theory and communication theory rely on applied probability. In the context of multi-user networks with new QoS metrics such as ultra reliable and low latency communications (URLLC), evaluating fundamental limits and properties of decentralized networks is an open problem. To make progress in this field, it is necessary to better understand some fundamental properties in applied probability.

In this context, we made progress in 2021 in three directions :

CDF of a sum of random vectors: The calculation of cumulative distribution functions (CDFs) of sums of random vectors is omnipresent in the realm of information theory. For instance, the joint decoding error probability in multi-user channels often boils down to the calculation of CDFs of random vectors. In the case of the memoryless Gaussian multiple access channel, under certain conditions on the channel inputs, the dependence testing bound corresponds to the CDF of a sum of independent and identically distributed (IID) random vectors. Unfortunately, the calculation of CDFs of random vectors requires elaborated numerical methods which often lead to unknown errors. From this perspective, approximations to these CDFs, e.g., Gaussian approximations and saddlepoint approximations have gained remarkable popularity. In the case of Gaussian approximations, multi-dimensional Berry-Esseen-type theorems provide upper bounds on the approximation errors. These bounds are particularly precise around the mean. Alternatively saddlepoint approximations are known to be more precise than Gaussian approximations far apart from the mean. Unfortunately, this claim is often justified only by numerical analysis as formal upper bounds on the error induced by saddlepoint approximations are rather inexistent. The PhD of Dadja Anade, co-supervised by Jean-Marie Gorce, Philippe Mary (INSA Rennes) and Samir Perlaza (Inria, NEO, Sophia Antipolis), contributed in this direction by introducing a real-valued function that approximates the CDF of a finite sum of real-valued IID random vectors. Both Gaussian and saddlepoint approximations are shown to be special cases of the proposed approximation, which is referred to as the exponentially tilted Gaussian approximation. The approximation error is upper bounded and both upper and lower bounds on the CDF are obtained [33, 45, 48].

Dependence between random variables through extreme values: In heavy-tailed data, such as data drawn from regularly varying models, extreme values can occur relatively often. As a consequence, in the context of hypothesis testing, extreme values can provide valuable information in identifying dependence between two data sets. In this paper, the error exponent of a dependence test is studied when only processed data recording whether or not the value of the data exceeds a given value is available. An asymptotic approximation of the error exponent is obtained, establishing a link with the upper tail dependence, which is a key quantity in extreme value theory. While the upper tail dependence has been well characterized for elliptically distributed models, much less is known in the non-elliptical setting. To this end, a family of nonelliptical distributions with regularly varying tails arising from shot noise is studied, and an analytical expression for the upper tail dependence derived [35].

Convergence guarantee of stochastic asynchronous optimization for a general class of objectives : Asynchronous distributed algorithms are a popular way to reduce synchronization costs in large-scale optimization, and in particular for neural network training. However, for non-smooth and nonconvex objectives, few convergence guarantees exist beyond cases where closed-form proximal operator solutions are available. As training most popular deep neural networks corresponds to optimizing nonsmooth and nonconvex objectives, there is a pressing need for such convergence guarantees. In this work, we analyze for the first time the convergence of stochastic asynchronous optimization for this general class of objectives. In particular, we focus on stochastic subgradient methods allowing for block variable partitioning, where the shared model is asynchronously updated by concurrent processes. To this end, we use a probabilistic model which captures key features of real asynchronous scheduling between concurrent processes. Under this model, we establish convergence with probability one to an invariant set for stochastic subgradient methods with momentum. From a practical perspective, one issue with the family of algorithms that we consider is that they are not efficiently supported by machine learning frameworks, which mostly focus on distributed data-parallel strategies. To address this, we propose a new implementation strategy for shared-memory based training of deep neural networks for a partitioned but shared model in single- and multi-GPU settings. Based on this implementation, we achieve on average about 1.2x speed-up in comparison to state-of-the-art training methods for popular image classification tasks, without compromising accuracy [39].

8.1.2 Contributions in Information Theory

Participants: Dadja Anade, Malcolm Egan, Jean-Marie Gorce, Hassan Kallam, Homa Nikbakht, Léonardo Sampaio Cardoso, Philipe Mary (INSA Rennes), Jean-Marc Kélif* (Orange Labs), Michèle Wigger* (IMT Paris), Shlomo Shamai* (Technion - Israel Institute of Technology).

Capacity for a channel with additive multivariate α-stable noise : A wide range of communication systems are corrupted by non-Gaussian noise, ranging from wireless to power line. In some cases, including interference in uncoordinated OFDMbased wireless networks, the noise is both impulsive and multivariate. At present, little is known about the information capacity and corresponding optimal input distributions. In this paper, we derive upper and lower bounds of the information capacity by exploiting non-isotropic inputs. For the special case of sub-Gaussian α-stable noise models, a numerical study reveals that isotropic Gaussian inputs can remain a viable choice, although the performance depends heavily on the dependence structure of the noise [27].

On second-order capacity of multi-delay constrained transmission of short packets : 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 before the decoding deadline. Nevertheless, this assumption fails when messages rapidly arrive and reliability constraints require that the number of channel uses exceeds the time between arrivals. In this paper, we study channel coding in this setting by jointly encoding messages as they arrive while decoding the messages separately, allowing for heterogeneous decoding deadlines. For a scheme based on power sharing, we analyze the probability of error in the finite blocklength regime. We show that significant performance improvements can be obtained for short packets by using our scheme instead of standard approaches based on time sharing [41, 51].

Capacity of the massive access channel with a continuum approach : Superposition coding (SC) has been known to be capacity achieving for the Gaussian memoryless broadcast channel for more than 30 years. However, SC regained interest in the context of non orthogonal multiple access (NOMA) in 5G. From an information theory point of view, SC is capacity achieving in the broadcast Gaussian channel, even when the number of users tends to infinity. But using SC has two drawbacks: decoders complexity increases drastically with the number of simultaneous receivers, and the latency is unbounded since SC is optimal only in the asymptotic regime. To evaluate these effects quantitatively in terms of fundamental limits, we introduce a finite time transmission constraint imposed at the base station and we evaluate fundamental trade-offs between the maximal number of superposed users, the coding block-length and the block error probability. The energy efficiency loss due to these constraints is evaluated analytically and by simulation. Orthogonal sharing appears to outperform SC for hard delay constraints (equivalent to short block-length) and in low spectral efficiency regime (below one bit per channel use). These results are obtained by the association of stochastic geometry and finite block-length information theory [29].

Topological interference management (TIM) in the intermediate SNR regime : In the PhD of Hassan Kallam [46], we propose a new interference topology construction approach, for the TIM problem of wireless networks, that extends TIM to the non-asymptotic SNR regime. We introduce a new framework that is able to control the interference topology more accurately and with more flexibility. With this approach, we are able to cope with the finite SNR regime and to evaluate the impact of the interference threshold used to build the interference topology.

Capacity with mixed delay traffic: We analyse the multiplexing gain (MG) achievable over Wyner's symmetric network with random user activity and random arrival of mixed-delay traffic. The mixed-delay 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. We derive inner and outer bounds on the MG region. In the limit as $D \to \infty$, the bounds coincide and the results show that transmitting delay-sensitive messages does not cause any penalty on the sum MG. For finite D our bounds are still close and prove that the penalty caused by delay-sensitive transmissions is small [42].

8.2 Axis 2: algorithms

8.2.1 Deep learning in wireless

Participants: Antoine Dejonghe, Jean-Marie Gorce, Claire Goursaud, Mathieu Goutay, Cyrille Morin, Léonardo Sampaio Cardoso, Fayçal Ait Aoudia* (Nokia Bell Labs), Carles Antón-Haro* (CTTC, Spain), Jakob Hoydis* (Nokia Bell Labs), Xavier Mestre* (CTTC, Spain).

rational : Machine learning (ML) starts to be widely used to enhance the performance of wireless transmissions. However, it is still unclear if such methods are truly competitive with respect to conventional methods in realistic scenarios and under practical constraints. These constraints are adaptability, complexity, but also signal processing constraints such as PAPR (Peak to Amplitude Power Ratio) or ACLR (Adjacent Channel Leakage Ratio). Our studies are described below:

P2P Scenario - Learning OFDM Waveforms with PAPR and ACLR Constraints : An attractive research direction for future communication systems is the design of new waveforms that can both support high throughputs and present advantageous signal characteristics. Although most modern systems use orthogonal frequency-division multiplexing (OFDM) for its efficient equalization, this waveform suffers from multiple limitations such as a high adjacent channel leakage ratio (ACLR) and high peak-to-average power ratio (PAPR). In this paper, we propose a learning-based method to design OFDM-based waveforms that satisfy selected constraints while maximizing an achievable information rate. To that aim, we model the transmitter and the receiver as convolutional neural networks (CNNs) that respectively implement a high-dimensional modulation scheme and perform the detection of the transmitted bits. This leads to an optimization problem that is solved using the augmented Lagrangian method. Evaluation results show that the end-to-end system is able to satisfy target PAPR and ACLR constraints and allows significant throughput gains compared to a tone reservation (TR) baseline. An additional advantage is that no dedicated pilots are needed [36, 49].

MU-MIMO Scenario - Learning receivers in OFDM Systems : In addition to enabling accurate signal reconstruction on realistic channel models, MU-MIMO receive algorithms must allow for easy adaptation to a varying number of users without the need for retraining. In contrast to existing work, we propose an ML-enhanced MU-MIMO receiver that builds on top of a conventional linear minimum mean squared error (LMMSE) architecture. It preserves the interpretability and scalability of the LMMSE receiver, while improving its accuracy in two ways. First, convolutional neural networks (CNNs) are used to compute an approximation of the second-order statistics of the channel estimation error which are required for accurate equalization. Second, a CNN-based demapper jointly processes a large number of orthogonal frequency-division multiplexing (OFDM) symbols and subcarriers, which allows it to compute better log likelihood ratios (LLRs) by compensating for channel aging. The resulting architecture can be used in the up- and downlink and is trained in an end-to-end manner, removing the need for hard-to-get perfect channel state information (CSI) during the training phase. Simulation results demonstrate consistent performance improvements over the baseline which are especially pronounced in high mobility scenarios [30, 37].

NOMA-MIMO Scenario - Learning the decoding ordering of multiple users : The user clustering problem in an uplink MIMO Non-Orthogonal Multiple Access (NOMA) scheme is considered here. The receiver is assumed to operate in two sequential stages that employ Linear Minimum Mean Squared Error (LMMSE) receivers. At the first stage, the receiver is designed to recover the transmission from a cluster of selected users/nodes. The contribution of these users is then subtracted from the received signal and the remaining user transmissions are then linearly recovered. The determination of which users should be detected during the first stage is formulated as a deep learning based multiple classification problem. In order to guarantee that the selection is robust to fast fading, the input to the neural network is based on second order channel statistics. Furthermore, the training process is simplified by using a large system approximation of the resulting sum-rates. Simulation results indicate that the proposed deep learning-based solution is able to achieve a significant rate advantage with respect to other lazy approaches, such as fixed or random cluster assignments [34]

2-user MAC Scenario - Joint Learning of constellations : Multiple access channel (MAC) is the theoretical basis for NOMA, that is a key technology for future cellular communications, expected to increase the number of devices served with a limited spectrum and to facilitate low latency communications. Yet the non-orthogonal operation leads to challenging interference conditions that require dedicated solutions, and this is particularly true for the constellations used to encode transmitted messages. The work developed in the last chapter of Cyrille Morin 's PhD uses deep learning to learn constellations tailored to the two-user MAC Gaussian channel, allowing for better performance than previously designed constellations, or the traditional orthogonal approach, stepping beyond the time-division multiple access (TDMA) capacity region. In the process, it also showcases the importance of performance comparison between orthogonal and non orthogonal approaches, and of studying the trade-offs between the two users, instead of focusing on aggregated metricsv[47].

8.2.2 Toward grant-free access and protocol-free

Participants: Dadja Anade, Lélio Chetot, Malcolm Egan, Jean-Marie Gorce, Cyrille Morin, Amaury Paris, Mateus Pontes Mota, Laurent Clavier*, IMT Lille-Douai, Alban Goupil*, U. Reims, Anders E Kalør*, Aalborg U. Denmark, Petar Popovski*, Aalborg U. Denmark, Philippe Mary*, INSA Rennes, Yasser Mestrah*, IMT Lille-Douai, Anne Savard*, IMT Lille-Douai, Alvaro Valcarce* (Nokia Bell Labs), Ce Zheng*, IMT Lille-Douai.

rational : A classical setup in NOMA massive access for IoT is that the nodes may request to transmit a packet at any time. A pure random access may leed to collisions or interference, which can be taken into account by developping robust detection, distributed optimization strategies or efficient distributed coding . Further, reducing signaling is of primary interest since in IoT, information to be sent may be small. In this general configuration we contributed to five studies as described below: Note that this setup is also the reference scenario chose to explore the use of Quantum algorithms (see section 8.2)

Joint sensor identification and channel estimation in narrowband communication systems: In this work, we develop algorithms for sensor identification and channel estimation in narrowband communication systems which is a necessary step in a standard NB-IoT protocol for instance. In our model we integrate a fault probability, which depends on physical variables and may be statistically correlated. The first step is to introduce a statistical model relating observations at the access point to the channel, activity of each sensor, and the probability each machine is faulty. Based on our new model, we derive an identification and channel estimation algorithm by exploiting GAMP by developing a loopy BP (LBP) algorithm for the model, and then applying GAMP for the variables associated with the communication channel. A key feature of the algorithm is that it explicitly accounts for uncertainty and correlation in the probability sensors are active, as opposed to existing approaches where the activity probability is fixed and sensor transmissions are uncorrelated. In addition, our model accounts for the impact of physical variables (such as temperature) on the probability of a fault. We model the probability of a fault conditioned on temperature observations at the access point via the beta distribution, a highly flexible family of models. As such, we call the algorithm β -HGAMP. Numerical results demonstrate that β -HGAMP outperforms existing algorithms based on GAMP and GS-HGAMP [23].

Resource optimization of random access for transmitters with correlated activation : For a range of scenarios arising in sensor networks, control and edge computing, communication is event-triggered; that is, in response to the environment of the communicating devices. A key feature of device activity in this setting is correlation, which is particularly relevant for sensing of physical phenomena such as earthquakes or flooding. Such correlation introduces a new challenge in the design of resource allocation and scheduling for random access that aim to maximize throughput or expected sum-rate, which do not admit a closed-form expression. In this work, we develop stochastic resource optimization algorithms to design a random access scheme that provably converge with probability one to locally optimal solutions of the throughput and the sum-rate. A key feature of the stochastic optimization algorithm is that the number of parameters that need to be estimated grows at most linearly in the number of devices. We show via simulations that our algorithms outperform existing approaches in terms of the expected sum-rate by up to 30% for a moderate number of available slots [32, 44].

Emergence of Wireless MAC Protocols with Multi-Agent Reinforcement Learning : This scenario is not exactly a grant-free access since a signaling channel exists. However, the protocol is not known in advance and we let the nodes learn the protocol through a learning phase based on decentralized reinforcement learning. We thus ropose a new framework, exploiting the multi-agent deep deterministic policy gradient (MADDPG) algorithm, to enable a base station (BS) and user equipment (UE) to come up with a medium access control (MAC) protocol in a multiple access scenario. In this framework, the BS and UEs are reinforcement learning (RL) agents that need to learn to cooperate in order to deliver data. The network nodes can exchange control messages to collaborate and deliver data across the network, but without any prior agreement on the meaning of the control messages. In such a framework, the agents have to learn not only the channel access policy, but also the signaling policy. The collaboration between agents is shown to be important, by comparing the proposed algorithm to ablated versions where either the communication between agents or the central critic is removed. The comparison with a contention-free baseline shows that our framework achieves a superior performance in terms of goodput and can effectively be used to learn a new protocol [50].

Optimal receiver in additive impulsive noise In axis 1, we studied the capacity of channels with additive impulsive noise. In axis 3, we conducted experimentation to show evidence that this model may be relevant in random access networks. Here, we developed a new receiver adapted to the characteristics of such channel. We focus on an unsupervised estimation of an approximation of the log-likelihood ratio in the finite block length regime with unknown noise distribution. We first analyze what conditions lead to estimation failure, derive an analytical tool to assess the failure probability, and then propose to jointly use two mechanisms that significantly reduce the estimation errors. Our estimation is shown to be efficient and the proposed receiver exhibits a near-optimal performance under various noisy environment types, ranging from very impulsive to Gaussian. We also show that short LDPC codes do not achieve the performance bound predicted by the finite block length analysis. This advocate for further investigations in short block length channel coding research [40].

8.3 Axis 3: experimental assessment

8.3.1 Experimenting with Cortexlab

Participants: Malcolm Egan, Paul Estève, Mohamad Gritli, Jean-Marie Gorce, Cyrille Morin, Amaury Paris, Léonardo Sampaio Cardoso.

rational : The work described in this section is complementary to the work described in section 7 and gives the scientific rational of the software developed in Maracas.

CorteXlab provides a unique worldwide testbed with free access to develop and tests new radio waveforms and MAC protocols without any standard limitation. The hardware is the unique limitation. Everything is software after I/Q signals processing. Our objetive is to develop collaborations to position CorteXlab as a necessary passage for reproducible research, especially with the growing interest in machine learning based approaches.

The contributions of the year are :

Lora multi-user framework : We developed a complete GNU Radio, dynamic and customizable physical (PHY) layer for long range (LoRa) transceiver, usable with the FIT/CorteXlab radio testbed and derived from the original EPFL LoRa implementation. The created adaptation, through a standardized interface, allows end-users an easy connection to an external medium access control (MAC)/upper layer to experiment scenarios in a fully reproducible and isolated environment. It also provides several PHY layer key performance indicators and metrics such as signal to noise ratio (SNR), received signal energy, binary error rate (BER) and other, that can be used to gauge the performance of the ongoing communications as well as construct MAC layers able to use this information. Finally, the interface allows our plug&play PHY solution to be used with any existing or newly adapted MAC layer, without having to implement it in GNU Radio [43]. A new software (Cortexlab_LORA_PHY) has been built.

ML based radio identification : During the PhD of Cyrille Morin [47], we develop an experimentation to try to train a Convolutional Neural Network (CNN) classifier using raw IQ samples without preprocessing and from experimental datasets to ensure that all possible features in the signal can be used by the neural network. The network is made to cope with the channel variation effects natively, without having to introduce any form of additional information at the transmitter, by purposely introducing channel variations in the training dataset. The approach used here can be seen as a data augmentation technique, but with the augmentation of channel parameters being from physical changes in the experimentation room, not through a simulated channel model.

Radio link statistics in interference environment With the internship of Mohamad Gritli (supervised by M. Egan and D. Gesbert), we evaluated the transmission pattern in uncoordinated IoT networks on CorteXlab.

Coded caching in single server multi-user scenario : In [28], vwe proposed an extended coded caching scheme based on piggyback coding for single-server multi-user networks with decentralized caching. The proposed scheme is obtained by adapting Polar codes and extending the original coded caching scheme, which is based on index coding and a data assignment that can be implemented via minimum graph-colouring. Polar codes are adapted so that users can apply parts of their cache contents as the frozen bits for Polar decoding, and the coded caching is adapted so as to account for different user coding rates and to combine transmissions to cache-aided and cache-free users. Numerical simulations prove that our piggyback-coding based scheme achieves higher rates than previous schemes also in the finite block-length regime. Importantly we contributed in the design and the evaluation of real testbed measurements validating the practical implementation.

8.3.2 Real world experimentation

Participants: Malcolm Egan, Laurent Clavier* (IMT Lille-Douai), Troels Pedersen* (Aalborg U. Denmark), Ignacio Rodriguez* (Aalborg U. Denmark), Mads Lauridsen* (Nokia Bell Labs).

rational : Despite the interest of CorteXlab, it may be very useful to also try and test real environments. We try to conduct such work in collaboration with Aalborg Unversity and IMT Lille-Douai [24]. In IoT, as not all devices are coordinated, there are limited opportunities to mitigate interference. As such, it is crucial to characterize the interference in order to understand its impact on coding, waveform and receiver design. While a number of theoretical models have been developed for the interference statistics in communications for the IoT, there is very little experimental validation. In this work, we addressed this key gap in understanding by performing statistical analysis on recent measurements in the unlicensed 863 MHz to 870 MHz band in different regions of Aalborg, Denmark. In particular, we show that the measurement data suggests the distribution of the interference power is heavy tailed, confirming predictions from theoretical models which confirm our working assumptions (see related contributions in axes 1 and 2).

8.4 Axis 4 : side roads exploration

In this *open-mind* research area, we developed two research axes. Both of them have been founded by research exploratory actions form Inria.

8.4.1 Molecular communications

Participants: Malcolm Egan, Bayram Akdeniz (now with U. of Oslo), Bao Tang* (Karl-Franzens-Universität, Graz, Autriche).

This research was partly funded with an exploratory action that ended in 2020, and founded the postdoc of Bayram Akdeniz. The publications of the year extended the former work as follows:

General overview and challenges : Chemical reactions and diffusion are two basic mechanisms governing the dynamics of molecules in a fluid. As such, they play a critical role in molecular communication for channel modeling, design of detection rules, implementation of molecular circuits for computation, and modeling interactions with external biochemical systems. For finite numbers of information-carrying molecules, stochastic models naturally arise with the simplest example given by the Wiener process, often known as Brownian motion. Nevertheless, the Wiener process fails to be accurate when external forces, friction, and chemical reactions are present. Recently, there have been several contributions that tailor molecular communication systems to these more challenging channel conditions. In this paper, we first overview a general family of stochastic models of reaction and diffusion systems, including both Langevin diffusion and the reaction-diffusion master equation. These models form a basis for the use of these models as molecular communication channels, from which modulation and detection schemes can be developed. We survey recent results on the design of these schemes, with a focus on a recently developed approach which is robust to a wide range of channel models, known as equilibrium signaling. We then turn to the implementation of these detection schemes and related parameter estimation problems via stochastic molecular circuits, based on stochastic chemical reaction networks. Finally, interactions between molecular communication systems and stochastic biological systems as well as open problems are discussed. Our overarching goal is to highlight how the consideration of general stochastic models of reaction and diffusion can be utilized in order to widen the application of molecular communications both within engineered systems, and also as motivation for advances in the mathematical characterization of these models. [27]

Estimation of equilibrium states of biochemical processes : A basic problem in molecular biology is to estimate equilibrium states of biochemical processes. To this end, advanced spectroscopy methods have been developed in order to estimate chemical concentrations in situ or in vivo. However, such spectroscopy methods can require special conditions that do not allow direct observation of the biochemical process. A natural means of resolving this problem is to transmit chemical signals to another location within a lab-on-a-chip device; that is, employing molecular communication in order to perform spectroscopy in a different location. In this paper, we develop such a signaling strategy and estimation algorithms for equilibrium states of a biochemical process. In two biologically-inspired models, we then study via simulation the tradeoff between the rate of obtaining spectroscopy measurements and the estimation error, providing insights into requirements of spectroscopy devices for high throughput biological assays [22].

Equilibrium Signaling in Spatially Inhomogeneous Diffusion and External Forces : Complex fluid media where molecules are susceptible to forces due, for example, to external magnetic fields, complicates the design of molecular communication systems. In particular, the equations governing the motion of each molecule in time do not typically admit tractable solutions, which makes receiver design challenging for standard communication schemes; e.g., based on concentration shift keying. In this paper, a new communication scheme is proposed, which leads to simple expressions for receiver statistics, even when spatially inhomogeneous diffusion and external forces are present. The proposed scheme exploits the equilibrium statistics of the system, which arise in a wide range of scenarios. This approach is illustrated in a bounded system with inhomogeneous diffusion and external forces determined by a quadratic potential [26].

8.4.2 Quantum information

Participants: Claire Goursaud, Muhammad Habibie, Jihad Hamié.

On going work : The field of quantum information science may revolutionize numerous information processing applications. Indeed, quantum information may lead to fast algorithms for complex computational problems and may help to design new communication protocols. Our research direction is to evaluate the potential of quantum information in the core of wireless communication protocols.

We started by exploring the use of quantum algorithms in the grant-free massive access in IoT explored in axis 2.

Quantum algorithms for multi-user detection in massive access : To support multiple transmissions in an optical fiber, several techniques have been studied such as Optical Code Division Multiple Access (OCDMA). In particular, the incoherent OCDMA systems are appreciated for their simplicity and reduced cost. However, they suffer from Multiple Access Interference (MAI), which degrades the performances. In order to cope with this MAI, several detectors have been studied. Among them, the Maximum Likelihood (ML) detector is the optimal one but it suffers from high complexity as all possibilities have to be tested prior to decision. However, thanks to the recent quantum computing advances, the complexity problem can be circumvented. Indeed, quantum algorithms, such as Grover, exploit the superposition states in the quantum domain to accelerate the computation. Thus, in this paper, we propose to adapt the quantum Grover's algorithm in the context of MUD, in an OCDMA system using non-orthogonal codes. We propose a way to adapt the received noisy signal to the constraints defined by Grover's algorithm. We further evaluate the probability of success in detecting the active users for different noise levels. Aside from the complexity reduction, simulations show that our proposal has a high probability of detection when the received signal is not highly altered. We show the benefits of our proposal compared to the classical and the optimal ML detector [38].

8.4.3 Beyond communications

Participants: Malcolm Egan.

A key problem for many industrial processes is to limit exposure to system malfunction. However, it is often the case that control cost minimization is prioritized over model identification. Indeed, model identification is typically not considered in production optimization, which can lead to delayed awareness and alerting of malfunction. In this paper, we address the problem of simultaneous production optimization and system identification. We develop new algorithms based on modifier adaptation and reinforcement learning, which efficiently manage the tradeoff between cost minimization and identification. For two case studies based on a chemical reactor and subsea oil and gas exploration, we show that our algorithms yield control costs comparable to existing methods while yielding rapid identification of system degradation [31].

9 Bilateral contracts and grants with industry

9.1 Bilateral contracts with industry

Participants: Naveed Ahmad -NoValue--NoValue- -NoValue- *(-NoValue-)*Lelio Chetot , Malcolm Egan , -NoValue--NoValue- -NoValue- *(-NoValue-)*Jean-Marie Gorce , Alix Jeannerot , -NoValue--NoValue- -NoValue- *(-NoValue-)*Cyrille Morin , Homa Nikbakht , -NoValue--NoValue- -NoValue- *(-NoValue-)*Léonardo Sampaio Cardoso .

We have currently the following partnerships

1. Inria-Nokia Bell Labs common lab (600k€) : we are involved in two research actions; Analytics and Network Information Theory. They cover the funding of two PhDs (Cyrille Morin and Lelio Chetot), a partial funding of another PhD (Alix Jeannerot) and 1 postdoc (Homa Nikbakht) for Maracas.
2. SPIE-ICS (1Meuros, 2017-2021) : The Insa-Spie IoT Chair IoT chair relies on the expertise of the CITI Lab. The skills developed within the different teams of the lab integrate study, modeling, conception and evaluation of technologies for communicating objects and dedicated network

architectures. It deals with network, telecom and software matters as well as societal issues such as privacy. The SPIE-ICS / Insa Lyon chaire on IoT has been setup in 2017 by JM Gorce for the benefit of the CITIlab. JM Gorce was the head of this chair from 2016 to 2019 and is now vice-head. Frédéric Le Mouel is heading the chair since sept 2019. The remaining budget for Maracas corresponds to one postdoc (Naveed Ahmad).

9.2 Bilateral grants with industry

1. CIFRE Nokia Bell Labs (2019-2022): PhD of Mathieu Goutay.

2. CIFRE Nokia Bell Labs (2021-2024): PhD of Shashwat Mitra.

10 Partnerships and cooperations

10.1 International initiatives

10.1.1 Participation in other International Programs

PHC Amadeus: M. Egan (visiting programme with Univ. Graz - B.Q. Tang and K. Fellner)

PHC Pavle Savic: JM. Gorce, L. Cardoso, C. Goursaud (visiting programme with D. Vukobratovic from Univ. of Novi Sad, Serbia - Dejan Vukobratovic)

Maracas is participating to the COST INTERACT CA20120 on Intelligence-Enabling Radio Communications for Seamless Inclusive Interactions. Start date: 18/10/2021 – End date: 17/10/2025.

10.2 European initiatives

10.2.1 FP7 and H2020 projects

- Windmill project : Maracas is a non-funded partner in Windmill and co-advise with Alvaro Valcarce (Nokia Bell Labs) the PhD of Mateus Pontes Mota. WindMill is a European Training Network (ETN) project within the framework of the H2020 Marie Skłodowska-Curie Innovative Training Networks (ITNs). The research in WindMill is about the integration of two research fields: wireless communications and machine learning. The overall research objective is the development of new methodologies based on machine learning in the design of wireless systems, while also contributing to the advancement of applied ML science. The achievement of the ultimate scientific objectives of the WindMill project will be pursued by the accomplishment of the following, more specific goals: Advancing the field of ML for wireless communications, Prediction schemes and anticipatory optimisation for fast-varying processes, Data-driven optimisation schemes for radio access management, System-wide “cognitive” optimisation schemes.

10.3 National initiatives

10.3.1 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.

- ANR ARBURST *Acheivable region of bursty wireless networks* (2016-2022, 195 KEuros, leader : Maracas, INSA-Lyon). In this project, we propose an original approach complementary to other existing projects, devoted to the study of IoT networks fundamental limits. Instead of proposing one specific technical solution, our objective is to define a unified theoretical framework. We aim at establishing the fundamental limits for a decentralized system in a bursty regime which includes short packets of information and impulsive interference regime. We are targeting the fundamental limits, their mathematical expression (according to the usual information theory framework capturing the capacity region by establishing a converse and achievability theorems). We will use the recent results relative to finite block-length information theory and we will evaluate the margin for improvement between existing approaches and these limits and we will identify the scientific breakthrough that may bring significant improvements for IoT/M2M communications. This project will contribute to draw the roadmap for the development of IoT/M2M networks and will constitute a unified framework to compare existing techniques, and to identify the breakthrough concepts that may afford the industry the leverage to deploy IoT/M2M technical solutions.

- ANR EquipEx FIT/CorteXlab (2009-2021, 1M€, leader : UPMC). The FIT projet is a national equipex headed by the Lip6 laboratory. As a member of Inria, Maracas is in charge of the development of the Experimental Cognitive Radio platform (CorteXlab) that is used as a testbed for SDR terminals and cognitive radio experiments. This has been operational since 2014 and is maintained for a duration of 7 years. To give a quick view, the user will have a way to configure and program through Internet several SDR platforms (MIMO , SISO , and baseband processing nodes). Thid plateform is now part of the European initiative "Slices".

10.3.2 Prospective projects

- SILECS 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.

- BPI – France Relance – 5G Events Labs [Consortium: CEA – Centre de Saclay, Ericsson, Inria, Orange] [2021–23]. 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

11 Dissemination

11.1 Promoting scientific activities

11.1.1 Scientific events: organisation

General chair, scientific chair: Jean-Marie Gorce was co-chair of the track Operational and Experimental Insights (OPE), at EuCNC and 6G summit, 8-11 June, 2021.

Member of the organizing committees: Leonardo S. Cardoso was organizer and member of the Scientific Commitee of the European GNU Radio Days 2021, June, 2021, Poitiers, France.

Jean-Marie Gorce co-organized a GDR ISIS scientific meeting on "Short packet transmission for wireless communications". ISEP Paris, 24-11-2021.

11.1.2 Scientific events: selection

Member of the conference program committees: Malcolm Egan was member of IEEE GLOBECOM 2021 and ACM NANOCOM 2021.

Jean-Marie Gorce was member of ICT2021.

11.1.3 Journal

Member of the editorial boards Malcolm Egan - Associate Editor, IEEE Communications Letters

Jean-Marie Gorce - associate editor of Entropy (MDPI) and Eurasip JWCN.

Claire Goursaud - associate editor of European Transactions on Telecommunications (ETT) and of Internet Technol. Letters (ITL)

Reviewer - reviewing activities Maracas members are regular reviewers of the main journals in our fields : IEEE Communications Letters, IEEE Wireless Communication Letters, IEEE Journal on Selected Areas in Communications, IEEE Journal on Selected Topics in Signal Processing, IEEE Sensors, IEEE Internet of Things Journal, IEEE Trans on Communications, IEEE Trans on Information Theory, IEEE Trans. on Mobile Computing, IEEE Trans on Molecular Biological, IEEE Trans on NanoBioscience, IEEE Trans on Signal Processing, IEEE Trans on Vehicular Technologies, IEEE Trans on Wireless Communications and Multi-Scale Communications, EURASIP Journal on Advances in Signal Processing, EURASIP Journal on Wireless Communications and Networking.

11.1.4 Invited talks

Malcolm Egan, "An Information Theoretic Perspective on Molecular Communication and the Role of Convergence to Equilibrium", Applied Analysis Seminar, University of Graz, Graz, Austria, (2021).

Malcolm Egan, "Stochastic Reaction-Diffusion Systems in Molecular Communication: Channel Models, Inference, and Coexistence", International Symposium on Molecular and Biological Communications, VNIT, Nagpur, India, (2021) [Invited 2h tutorial, presented online].

Jean-Marie Gorce, "NB-IoT framework for GNU Radio experimentation in CorteXlab", European GNU radio days (2021).

11.1.5 Scientific expertise

JM Gorce is a member of the Commission d'évaluation (CE), Inria.

JM Gorce was a member of a Professor recruitment Committee at ENSEA, Cergy, and an Ass. Professor recruitment Committee at IMT Lille-Douai.

JM Gorce was vice-chair of the recruitment committee of CRCN and ISFP at Inria Lyon.

JM Gorce was a member of the recruitment committee of CRCN And ISFP at Inria Rennes.

C. Goursaud is a member of the commission nationale des universités (CNU), in section 61.

11.1.6 Research administration

JM Gorce is head for research at the Inria Lyon centre.

M Egan is a member of the scientific committee of CITIlab.

C Goursaud is vice-director of CITIlab.

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 ativity.

- 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, M Egan, L Chetot, J Hamié - Advanced Digital Communications, M1, Telecommunications dept, INSA Lyon, France.
- Master : J Hamié, A Paris - Radio Access Networks, 32h eqTD, M1, Telecommunications dept, INSA Lyon, France.
- Master : L Cardoso, C Morin - Software Radio, 32h eqTD, M2, Telecommunications dept, INSA Lyon, France.
- Master : C Goursaud - Communications Systems, 32h eqTD, M1, Telecommunications dept, INSA Lyon, France.

11.2.2 Supervision

PhDs defended in 2021

- Cyrille Morin : Deep learning based approaches for detection in physical layer wireless multiple access; 22, July, 2021. sup: L. Sampaio Cardoso, J. Hoydis, JM. Gorce.
- Hassan Kallam : Topological Interference Management for Multi-User Wireless Networks; 28, September, 2021. sup: L. Sampaio Cardoso, JM Gorce.
- Dadja Anade : Contributions to the Analysis of Communications Systems in the Finite Blocklength Regime; 7, October, 2021. sup: JM Gorce, P. Mary and S. Perlaza

PhDs in progress:

- José Rugelles (start Jan 2017): Deep Learning for Security in GSM Based IoT Systems. Sup: Léonardo S. Cardoso and Edward Guillén (U. of Colombia).
- Lélio Chetot (start Oct. 2018) : From finite blocklength information theory to multi-user M2M communication protocols. Sup: Malcolm Egan and Jean-Marie Gorce.
- Mathieu Goutay (start Feb. 2019) : Applications of Deep Learning to the Design of Enhanced Wireless Communication Systems. Sup: Jean-Marie Gorce and Jakob Hoydis (Nokia Bell Labs).
- Mateus Pontes Mota (start oct 2020) Sup: Jean-Marie Gorce and Alvaro Valcarce (Nokia Bell Labs).
- Idham Habibie (start nov. 2020) : Quantum algorithms for multi-user wireless communications. Sup: Claire Goursaud and Jihad Hamié.
- Alix Jeannerot (start oct 2021): Data-driven management of massive access IoT communicationnetworks. Sup. : Jean-Marie Gorce and Malcolm Egan.
- Guillaume Marthe (start oct 2021) : Spiking neurons for wireless communications. Sup : Claire Goursaud and Jihad Hamié.
- Shashwat Mishra (start oct 2021) : Machine Learning Empowered Massive Machine Type Communication for Industrial IoT and Beyond 5G Networks. Sup: Jean-Marie Gorce and Calvin Chen (Nokia Bell Labs).
- Mamadou Ngom (start dec 2021: Impulsive interference in b5g. Sup: M. Egan, L. Clavier.

Masters and internships

- Mohamad Gritli: Transmission pattern design in uncoordinated iot networks. Sup: Malcolm Egan
- Paul Estève: ON multi-user LoRa receiver in CorteXlab. sup: Amaury Paris, Léonardo Sampaio Cardoso.

11.2.3 Juries

Jean-Marie Gorce was in the jury of:

- Chair of the jury of the "Habilitation à diriger des recherches" of Mathieu Cunche : Privacy issues in wireless networks - Every frame you send, they'll be watching you; 2, June, 2021, INSA de Lyon.
- PhD Reviewer of David Pallier: Sensor Enhancement to Augmented Usage and Reliability; 10 march 2021, University of Nantes.
- Chair of the jury of Mariam El Hassan: Evaluation analytique des distorsions de signaux à porteuses multiples en présence d'amplification non-linéaire et en prenant en compte différentes techniques de réduction de la dynamique des signaux; 6 April 2021, Insa Rennes.
- Chair of the jury of Arthur Louchart: Allocation de ressources adaptées aux défauts de nonlinéarité des systèmes cognitifs par satellite; 7 December, 2021; IMT Paris Saclay.
- PhD Examiner of PXiaotian Fu: Scheme Design and Advanced Receivers for SCMA and Non-coherent MIMO in Future Wireless Networks; 9 December 2021; CNAM Paris.
- PhD Examiner of Yanni Zhou: On the Performance of Spatial Modulation and Full Duplex Radio Architectures; 10 December, 2021; Insa Lyon.

Claire Goursaud was in the jury of:

- Examiner of "Habilitation a diriger des recherche" of Charlotte Langlais : Rétroaction et interactions : des turbo-communications à l'apprentissage; 13, April, 2021.
- PhD Examiner of Cédric Bérenger: Grands réseaux maillés basse énergie, 14, January, 2021.
- PhD Reviewer of Esteban Silva : Numérisation, compression et reconstruction d'un trafic radio large échelle pour l'internet des objets, 10, June 2021
- PhD Reviewer of Wissal Ben Ameur : Etude des mécanismes d'accès multiples non orthogonaux pour le déploiement massif de l'IoT dans les futurs réseaux cellulaires, 25, May, 2021
- PhD Reviewer of Ahmed AbdelGhany : Purposely Exploiting the Channel in IoT, Enhancement of Localization and Spectrum Allocation in LPWAN, 8, December, 2021

12 Scientific production

12.1 Major publications

[1] G. C. Alexandropoulos, P. Ferrand, J.-M. Gorce and C. B. Papadias. 'Advanced coordinated beamforming for the downlink of future LTE cellular networks'. In: *IEEE Communications Magazine* 54.7 (July 2016). Arxiv: 16 pages, 6 figures, accepted to IEEE Communications Magazine, pp. 54–60. DOI: 10.1109/MCOM.2016.7509379. URL: https://hal.inria.fr/hal-01395615.

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[4] M. Egan, L. Clavier, C. Zheng, M. De Freitas and J.-M. Gorce. 'Dynamic Interference for Uplink SCMA in Large-Scale Wireless Networks without Coordination'. In: *EURASIP Journal on Wireless Communications and Networking* 2018.1 (Aug. 2018), pp. 1–14. DOI: 10.1186/s13638-018-1225-z. URL: https://hal.archives-ouvertes.fr/hal-01871576.

[5] M. Egan, J. Drchal, J. Mrkos and M. Jakob. 'Towards Data-Driven On-Demand Transport'. In: *EAI Endorsed Transactions on Industrial Networks and Intelligent Systems* 5.14 (June 2018), pp. 1–10. DOI: 10.4108/eai.27-6-2018.154835. URL: https://hal.archives-ouvertes.fr/hal-01839452.

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[9] I. Esnaola, S. Perlaza, H. V. Poor and O. Kosut. 'Maximum Distortion Attacks in Electricity Grids'. In: *IEEE Transactions on Smart Grid* 7.4 (2016), pp. 2007–2015. DOI: 10.1109/TSG.2016.2550420. URL: https://hal.archives-ouvertes.fr/hal-01343248.

[10] Y. Fadlallah, A. M. Tulino, D. Barone, G. Vettigli, J. Llorca and J.-M. Gorce. 'Coding for Caching in 5G Networks'. In: *IEEE Communications Magazine* 55.2 (Feb. 2017), pp. 106–113. DOI: 10.1109/MCOM.2017.1600449CM. URL: https://hal.inria.fr/hal-01492353.

[11] C. Genes, I. Esnaola, S. Perlaza, L. F. Ochoa and D. Coca. 'Robust Recovery of Missing Data in Electricity Distribution Systems'. In: *IEEE Transactions on Smart Grid* (2018).

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[13] C. Goursaud and J.-M. Gorce. 'Dedicated networks for IoT : PHY / MAC state of the art and challenges'. In: *EAI endorsed transactions on Internet of Things* (Oct. 2015). DOI: 10.4108/eai.26-10-2015.150597. URL: https://hal.archives-ouvertes.fr/hal-01231221.

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[19] V. Quintero, S. Perlaza, I. Esnaola and J.-M. Gorce. 'Approximate Capacity Region of the Two-User Gaussian Interference Channel with Noisy Channel-Output Feedback'. In: *IEEE Transactions on Information Theory* 64.7 (July 2018). Part of this work was presented at the IEEE International Workshop on Information Theory (ITW), Cambridge, United Kingdom, September 2016 and IEEE International Workshop on Information Theory (ITW), Jeju Island, Korea, October, 2015. Parts of this work appear in INRIA Technical Report Number 0456, 2015, and INRIA Research Report Number 8861., pp. 5326–5358. DOI: 10.1109/TIT.2018.2827076. URL: https://hal.archives-ouvertes.fr/hal-01397118.

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12.2 Publications of the year

International journals

[22] B. C. Akdeniz and M. Egan. 'Molecular Communication for Equilibrium State Estimation in Biochemical Processes on a Lab-on-a-Chip'. In: *IEEE Transactions on NanoBioscience* (2021). URL: https://hal.archives-ouvertes.fr/hal-03151618.

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