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2025 *Activity Report*

RESEARCH CENTRE: **Inria Lyon Centre**

IN PARTNERSHIP WITH: **Institut national des sciences appliquées de Lyon**

Project-Team

MARACAS

Models and Algorithms for Reliable Communication Systems

In collaboration with Centre d’innovation en télécommunications et intégration de services

Project-Team MARACAS

Creation of the Project-Team: 2020 January 01

Each year, Inria research teams publish an Activity Report presenting their work and results over the reporting period. These reports follow a common structure, with some optional sections depending on the specific team. They typically begin by outlining the overall objectives and research programme, including the main research themes, goals, and methodological approaches. They also describe the application domains targeted by the team, highlighting the scientific or societal contexts in which their work is situated. The reports then present the highlights of the year, covering major scientific achievements, software developments, or teaching contributions. When relevant, they include sections on software, platforms, and open data, detailing the tools developed and how they are shared. A substantial part is dedicated to new results, where scientific contributions are described in detail, often with subsections specifying participants and associated keywords. Finally, the Activity Report addresses funding, contracts, partnerships, and collaborations at various levels, from industrial agreements to international cooperations. It also covers dissemination and teaching activities, such as participation in scientific events, outreach, and supervision. The document concludes with a presentation of scientific production, including major publications and those produced during the year.

Keywords

Computer sciences and digital sciences

A1.2.6. – Sensor networks

A1.2.10. – Digital Communications

A1.5.2. – Communicating systems

A2.3.2. – Cyber-physical systems

A2.3.3. – Real-time systems

A3.4. – Machine learning and statistics

A5.9.2. – Estimation, modeling

A5.9.5. – Sparsity-aware processing

A5.9.6. – Optimization tools

A7.1.1. – Distributed algorithms

A7.1.4. – Quantum algorithms

A8.2.6. – Numerical methods for optimization

A8.6. – Information theory

A8.8. – Network science

A9.2. – Machine learning

A9.2.1. – Supervised learning

A9.2.2. – Unsupervised learning

A9.2.3. – Reinforcement learning

A9.2.5. – Bayesian methods

A9.2.6. – Neural networks

A9.2.8. – Deep learning

A9.3. – Signal processing

A9.9. – Distributed AI, Multi-agent

Other research topics and application domains

B1.1.10. – Systems and synthetic biology

B4.5.1. – Green computing

B6.2.2. – wireless networks

B6.2.3. – Satellite networks

B6.2.4. – Optical networks

B6.2.5. – Non Terrestrial Networks

B6.2.6. – Cellular networks (3G,. . . 6G)

B6.4. – Internet of things

B6.6. – Embedded systems

B8.1. – Smart building/home

B8.2. – Connected city

Contents

1 Team members, visitors, external collaborators

Research Scientists

- Malcolm Egan [INRIA, Researcher]
- Maxime Guillaud [INRIA, Senior Researcher]

Faculty Members

- Claire Goursaud [Team leader, INSA LYON, Associate Professor, from May 2025, HDR]
- Jean-Marie Gorce [INSA LYON, Professor, until Apr 2025, HDR]
- Leonardo Sampaio [INSA LYON, Associate Professor]
- Kevin Zagalo [INSA LYON, ATER, from Sep 2025]

Post-Doctoral Fellows

- Anil Kumar [INRIA, Post-Doctoral Fellow, from Mar 2025]
- Kassem Saied [Insa Lyon, from Feb 2025, CITI Laboratory]
- Yamil Vindas Yassine [INRIA, Post-Doctoral Fellow, until Apr 2025]
- Kevin Zagalo [INRIA, Post-Doctoral Fellow, until Aug 2025]

PhD Students

- Sih-Yu Chou [INRIA, from Oct 2025]
- Loukas Duque [INRIA]
- Oussama Harrak [INRIA, from Feb 2025]
- Tan Khiem Huynh [INRIA]
- Andrea Joly [INRIA]
- Mohamed El Mehdi Makhlouf [INRIA]
- Claire Mesny [ORANGE, CIFRE]
- Romain Piron [INSA LYON, until Sep 2025]
- Sweta Suresh [INRIA, from Feb 2025]
- Samya Tannir [UBL]
- Shanglin Yang [ORANGE, CIFRE, until Aug 2025]

Technical Staff

- Mariam Ahhttouche [INRIA, Engineer, from Feb 2025]
- Pascal Girard [INSA LYON, Engineer]
- Matthieu Imbert [INRIA, Engineer]
- Muhammad Jehangir Khan [INRIA, Engineer, until Jan 2025]
- Cyrille Morin [INRIA, Engineer]

Interns and Apprentices

- Johan Bartosik [INRIA, Intern, from May 2025 until Aug 2025]
- Julien Brelivet [INSA Lyon, from Sep 2025]
- Fabian Ganzer [INSA Lyon, until Feb 2025]

Administrative Assistants

- Cecilia Navarro [INRIA]
- Linda Soumari [INSA LYON]

External Collaborator

- Camila Vera Villa [IMFD Instituto Milenio Fundamentos de los Datos CHILE]

2 Overall objectives

2.1 Motivation

In the last decades, telecommunications have improved human connectivity, leading to a seamless worldwide coverage that has become indispensable to human activities. 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. In recent years, 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. New usages have also appeared, such as virtual reality, autonomous vehicles, or the widespread use of machine learning, giving rise to new classes of traffic with specific demands in terms of reliability, latency and throughput. Furthermore, the aforementioned classical network architecture based on a centralized approach are gradually becoming outdated: with the emergence of artificial intellingence (AI) applications often involves the ability for communications network to process data *en-route*, networks are shifting away from the classical “bit-pipe” paradigm to become distributed computing tools.

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: while learning approaches are not always competitive against heavily optimized model-based signal processing algorithms often found in communications systems, they can substantially outperform classical architectures in cases where the model is not or imperfectly known, which is often the case when dealing with physical systems (electronics, propagation, etc).
- 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. [54, 52, 64].

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 [18] 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, the 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

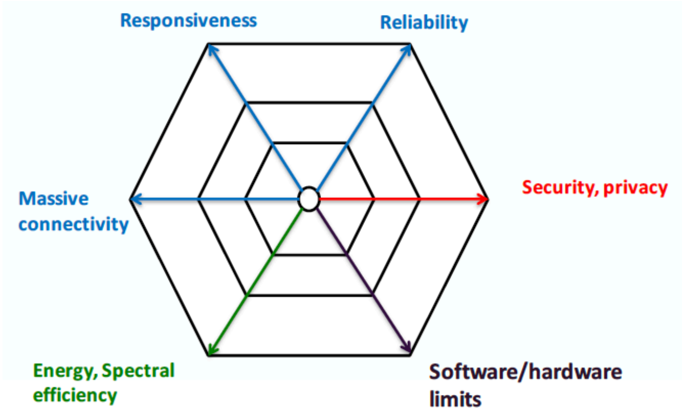

Figure 1: Main metrics for future networks (5G and beyond)

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 [61].

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 [60, 62] and in association with other tools devoted to the analysis of random processes (queuing theory, ...).

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

In particular, MARACAS combines techniques from communication and information theory with statistical signal processing, control theory, game theory and machine learning. 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 address 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.**

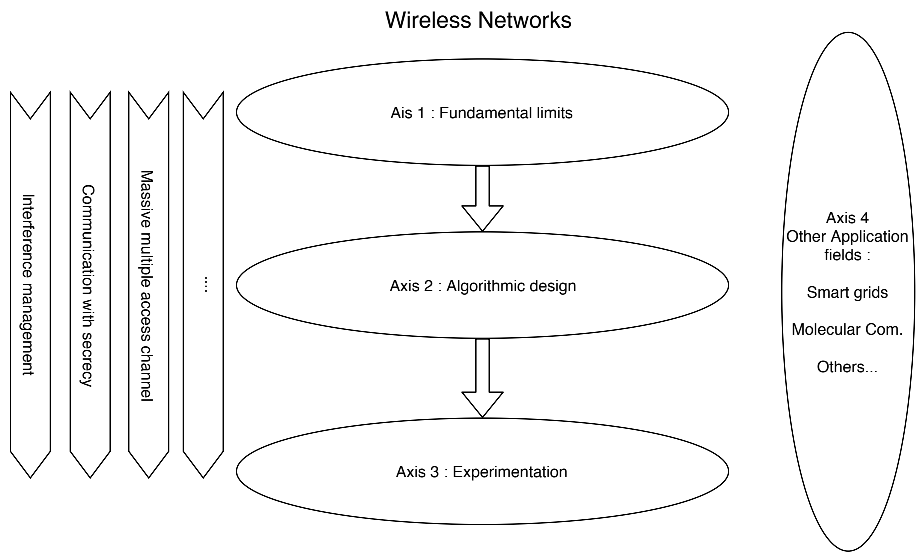

Figure 2: MARACAS organization

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 [6] of for multi-constrained systems [17].

  This also means revisiting the fundamental estimation-detection problem [63] 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* [51] 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*.

- **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 [66, 53].

  Another emerging research direction relies on using machine learning techniques [47] 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 (http://www.cortexlab.fr/), 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 [2, 8]. 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 [10] and the original paradigm of molecular communications [5].

  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 finalized 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 CITI lab, with the Dynamid team 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.
- Developing self-supervised learning methods for statistical processing of long-term propagation data (channel state information).
- 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. These equipments can be turned on only when an experiment is underway.
- Computer sustainability: we generally use computers for at least 5 years, and require extended warranty contracts (5 to 7 years) at the time of purchase.
- Travelling represents an important part of our CO_2 footprint. We strive to avoid frequent long-distance trips and encouraging extended stays including multiple research interactions in the same geographical area during trips involving long flights.

5.2 Impact of research results

We strive to design high-rate, high-QoS wireless protocols under stringent energy consumption contraints. Our research area includes solutions allowing to remove batteries from certain devices (zero-energy devices), as well as energy-efficient approaches which can potentially reduce the CO_2 footprint of future networks. However we acknowledge that the problem of energy consumption of communication networks is often ill-posed, since many results produced in our scientific community merely focus on improving energy efficiency without taking rebound effects into account.

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

6 Highlights of the year

6.1 Federated Learning

Participants: Malcolm Egan, Jean-Marie Gorce, Tan Khiem Huynh.

A central topic in MARACAS during 2025 was federated learning. This work was primarily carried out in the context of the Inria Challenges FedMalin and Learn-Net, and focused on both the convergence theory and applications in wireless communication networks. A key result published in NeurIPS 2025 established a general convergence theory for federated learning with Markovian data sources [33]. In the context of the Inria Learn-Net Challenge, MARACAS also organized a workshop for PhD students on federated learning.

6.2 Channel Charting

Participants: Maxime Guillaud, Mohamed El Mehdi Makhlouf, Anil Kumar.

Progress has been made on multiple aspects of the work on Channel Charting: we published the MOCSID dataset [36], developed a new weak supervision approach leveraging Doppler effect [35], and extended our work to charting in the presence of a reflective intelligent surface [37]. We co-organized a Workshop on Privacy in Wireless Communications in collaboration with the CHASER project.

6.3 Risk-Aware Data Compression

Participants: Malcolm Egan.

A key question for modern communication systems is how to tailor communication strategies for specific tasks, often known as goal-oriented or semantic communications. During 2025, in the context of the PEPR Réseau du futur and the ANR JCJC TCDTP projects, a new framework was established for goal-oriented communications which accounted for the risk associated with extreme events. A risk-aware framework was developed in detail for fixed-length source coding with risk measure distortion constraints, with fundamental information theoretic limits established in [32]. This framework was also utilized for the design of goal-oriented vector quantization schemes where the goal is imperfectly specified in [24].

6.4 Information-Theoretic Limits of Broadcast Channels

Participants: Malcolm Egan, Jean-Marie Gorce.

A core information-theoretic model is the broadcast channel, which plays a key role in understanding downlink communication channels. In [26] with collaborators at Princeton University, we established a finite blocklength characterization in the presence of heterogeous delay constraints, which captures scenarios where coding is applied to multiple messages that arrive at different times.

7 Latest software developments, platforms, open data

As part of its teaching and research experiments, both inside and outside of the CorteXlab platform, the team uses heavily the open source software GNU Radio. And as part of that use, Cyrille Morin occasionnaly contribues to the code, and with Leonardo Cardoso, contributes to the software's community by co-organising annual events such as the GNU Radio European Days. In 2025, Cyrille Morin was appointed as member of GNU Radio's general assembly.

7.1 Latest software developments

7.1.1 cortexlab-minus

Keywords: Middleware, Reproducibility, Experimental testbed

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

Participants: Matthieu Imbert, Mariam Ahhttouche

7.1.2 cortexlab-webapp

Keywords: Web Application, Collaborative resource management

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

Contact: Pascal Girard

7.1.3 CorteXlabTools

Name: Software toos for experimental testbed CorteXlab

Keywords: CorteXlab, SDR (Software Defined Radio), Machine learning

Functional Description: Software suite devoted to CorteXlab platform remotely accessible for everyobdy

News of the Year: Preparation for large scale refactoring and evolutions to prepare for platform rejuvenation as part of PEPR NF PC 10

URL: `http://www.cortexlab.fr`

Publication: hal-01101087

Contact: Leonardo Sampaio

Participants: Matthieu Imbert, Mariam Ahhttouche

7.1.4 RIS API

Keyword: Web API

Functional Description: Set of REST web servers and scripts to control the Greenerwave Reflective intelligent surface (RIS)'s API remotely. This RIS is installed inside of the CorteXlab radio room as part of the INSTINCT european project

Contact: Cyrille Morin

7.1.5 channel_monitoring

Keywords: GNU Radio, SDR (Software Defined Radio), Wave propagation, CorteXlab

Functional Description: This is primarily designed as a module for the GNU Radio framework. It makes use of existing GNU Radio blocks, as well as providing new ones to implement signal processing chains for measuring wireless propagation channel characteristics. It is comprised of a transmitter, sending a known packet of data at regular intervals, and a receiver listening for those packets, and using the way the known data was modified during transmission to estimate propagation characteristics. The receiver records the gathered data in a .sigMF file for later processing.

A number of parameters are offered as arguments, such as transmission period, centre frequency, bandwidth, ... And the system can also be setup to progressively sweep over a specified frequency range to gather wide band data.

This software also provides a Python processing suite to make use of the recorded data, and plot various metrics, such as frequency response, or time stability.

It can be used with any pair of Software Defined Radio equipment, in any location, but it is designed to operate inside of the CorteXlab room. For that reason, helper files and script are provided to facilitate running experiments in the CorteXlab platform.

URL: https://gitlab.inria.fr/cortexlab/measurements/channel_monitoring

Contact: Cyrille Morin

Participant: Cyrille Morin

7.2 New platforms

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

7.2.1 FIT/CorteXlab toward integration in SLICES/Europe

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

As the FIT project development phase ended in 2019 , CorteXlab has seen continued usage as well as further developments. FIT/CorteXlab has been used by both INSA and the European GNU Radio Days 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 2024, CorteXlab became a part of the SLICES-FR programm funded by PEPR NF/PC 10 PLATEFORMS, in coordination with Raymond Knopp from Eurecom, and Walid Dabbous from the team DIANA, Inria Sophia. This PEPR funding is aimed at platform rejuvenation to keep the platform relevant and up to date for research.

Preparation for the rejuvenation happened throughout 2025 with supporting software developpment and preparation of new hardware installation, culminating with an order of most of the computing hardware in december. The new deployment is expected in the first half of 2026.

Figure 3: FIT/CorteXlab facility

7.3 Open data

Channel Charting Outdoors Synthetic CSI Dataset The Multi-cell Outdoor Channel State Information Dataset (MOCSID) dataset was released. It contains synthetic wireless propagation data (a.k.a. channel state information, CSI) for the purpose of benchmarking channel charting algorithms such as those developed in the CHASER and INSTINCT projects. Specifically, CSI time series from 10k realistic user trajectories in a multi-cell outdoors (campus) environment have been simulated using the NVIDIA Sionna simulator, based on a 3D scene generated from OpenStreetMap data. The dataset is designed to ensure spatial consistency across the users, and to correctly model overlapping service areas, in order to allow the benchmarking of distributed multi-site channel charting algorithms. Link to MOCSID on Zenodo.

8 New results

As presented is section 3, the research program of MARACAS focuses on reliable communications for multi-user systems, in the context of computing networks. The project is organized in three main axes : i) fundamental limits of multi-user systems, ii) algorithms for efficient multi-user systems, iii) experimentation. A fourth axis covers cross-roads exploration as detailed in section 3.2.

However the research in MARACAS is not siloed. Typically a specific scenario (e.g. Grant free multiple access) is studied from theory to experimentation. To highlight these interactions between the different axes, our activity is organized through challenges.

In 2025, we have been involved on the following challenges

- Challenge 1: foundational results (leveraging on all axes): the objective of this challenge is to develop new models, new algorithms and new experimental setups at the service of current and future applications. These works are not necessarily application driven, but rather motivated by fundamental open questions.

- Challenge 2: IoT massive access and URLLC (leveraging on axes 1,2,3). Massive access is a keystone problem for 5G, 6G in the context of machine to machine communications. We explore fundamental bounds as well as new algorithms mostly based on machine learning, and we develop experimental setups.

- Challenge 3: PHY layer design (leveraging on axes 2,3). The objective is to deeply study and characterize the PHY layer properties and to design new waveforms, e.g. for IRS, for massive MIMO,...
- Challenge 4: Security and Energy (leveraging on axes 2,3). We study new technologies under the light of security and energy constraints at the radio level. Radio-based localisation is one of the key component.
- Challenge 5: Computing Networks (leveraging on all axes). In this axis we explored new paradigms mostly connected to decentralized estimation/detection problems, such as federated learning, with a focus on communication related questions.

In the following we present our activity per axis, referring to these 5 challenges. We do not present specific results on experimentation. Nevertheless, we highlight that a huge effort has been made to prepare the evolution of CorteXlab and to adapt it for the European Instinct project.

8.1 Axis 1 : Foundations of communication theory

Participants: Malcolm Egan, Jean-Marie Gorce, Maxime Guillaud.

In this axis, we addressed the following problems :

8.1.1 Streaming Federated Learning with Markovian Data

Participants: Malcolm Egan, Jean-Marie Gorce, Tan Khiem Huynh.

In [33], we developed convergence theory for federated learning systems with streaming data. Federated learning (FL) is now recognized as a key framework for communication-efficient collaborative learning. Most theoretical and empirical studies, however, rely on the assumption that clients have access to pre-collected data sets, with limited investigation into scenarios where clients continuously collect data. In many real-world applications, particularly when data is generated by physical or biological processes, client data streams are often modeled by non-stationary Markov processes. Unlike standard i.i.d. sampling, the performance of FL with Markovian data streams remains poorly understood due to the statistical dependencies between client samples over time. In this paper, we investigate whether FL can still support collaborative learning with Markovian data streams. Specifically, we analyze the performance of Minibatch SGD, Local SGD, and a variant of Local SGD with momentum. We answer affirmatively under standard assumptions and smooth non-convex client objectives: the sample complexity is proportional to the inverse of the number of clients with a communication complexity comparable to the i.i.d. scenario. However, the sample complexity for Markovian data streams remains higher than for i.i.d. sampling.

8.1.2 Broadcast channels with heterogeneous arrival and decoding deadlines: Second-order achievability

Participants: Malcolm Egan, Jean-Marie Gorce.

In [26], we established a finite blocklength characterization of achievable rates for broadcast channels with heterogeneous delay constraints. A standard assumption in the design of ultra-reliable low-latency communication systems is that the duration between message arrivals is larger than the number of channel uses before the decoding deadline. Nevertheless, this assumption fails when messages arrive rapidly and reliability constraints require that the number of channel uses exceed the time between arrivals. In this paper, we consider a broadcast setting in which a transmitter wishes to send two different messages to two receivers over Gaussian channels. Messages have different arrival times and decoding deadlines such that their transmission windows overlap. For this setting, we propose a coding scheme that exploits Marton's coding strategy. We derive rigorous bounds on the achievable rate regions. Those bounds can be easily employed in point-to-point settings with one or multiple parallel channels. In the point-to-point setting with one or multiple parallel channels, the proposed achievability scheme is consistent with the normal approximation. In the broadcast setting, our scheme agrees with Marton's strategy for sufficiently large numbers of channel uses and shows significant performance improvements over standard approaches based on time sharing for transmission of short packets.

8.1.3 Risk-Aware Estimation From Compressed Data Beyond the Bayes Risk

Participants: Malcolm Egan.

In [32], we established a framework for risk-aware data compression. Inference often relies on compressed data due to communication, storage, or privacy constraints. In order to minimize degradation in the quality of inference, it is desirable to tailor compression schemes to the inference task. The compression scheme should therefore account for the statistic of the loss relevant for the task. While the expected loss is widely considered, in applications sensitive to large losses—such as in safe control and learning—alternative statistics are relevant. A key family of these alternative statistics are obtained via risk measures. In this paper, we characterize the increase in risk measure criteria for inference tasks as a function of the code size. Our characterization applies for general data statistics, loss functions, and number of samples. In the special case of iid data, we also establish asymptotics and a connection between our characterization for risk measure criteria and the rate-distortion function, which was previously only known for expected loss and excess distortion criteria.

8.1.4 Performance evaluation of NOMA in multicell networks

Participants: Jean-Marie Gorce.

While the performance of NOMA has been well evaluated in the context of single cell, its evaluation at the network size is difficult because one have to combine NOMA with mobile-base station association strategies and resource sharing mechanisms. We proposed in [22] a versatile evaluation framework, able to assess the performance of multi-cell networks implementing a large variety of RSMs under a minimal set of assumptions. The proposed approach relies on Inspire, a black box Bayesian optimization framework developed by Anthony Bardou and Thomas Begin [46].

8.2 Axis 2 : Algorithms for MU networks

Participants: Malcolm Egan, Jean-Marie Gorce, Claire Goursaud, Maxime Guillaud, Cyrille Morin, Leonardo Sampaio.

8.2.1 Quantum algorithms for multiple access

Participants: Claire Goursaud, Romain Piron, Fabian Ganzer.

This line of research is more explorative, but is also focused on multi-user access (challenge 2). The objective is to explore the use of quantum alogrithms to optimize active user detections (AUD). This work was initiated with the PhD of Idham Habibie, funded by an Inria exploratory action [50]. This work has been extended to more realistic scenarios with the PhD of Romain Piron [38, 57, 58, 59]. Leveraging quantum annealing (QA) for the AUD problem in massive wireless networks is a promising approach to address the stringent reliability and latency constraints of typical application scenarios. First, in [58], we first propose a mapping between the AUD searching problem and the identification of the ground state of an Ising Hamiltonian. Then, we compare the execution times of our QA approach for several code domain multiple access (CDMA) scenarios. We evaluate the impact of the cross- correlation properties of the chosen codes in a NOMA network for detecting the active user's set. In [59] we show that the maximum a posteriori decoder of the activity pattern of the network can be seen as the ground state of an Ising Hamiltonian. For N users in a network with perfect channels, we propose a universal control function to schedule the annealing process. Our approach avoids to continuously compute the optimal control function but still ensures high success probability while demanding a lower annealing time than a linear control function. This advantage holds even in the presence of imperfections in the network.

However, the practical implementation of QA on current D-Wave's processors requires embedding the problem. This increases the number of qubits needed for a given network size, which degrades QA performance. In [38], we propose to add a pre-processing step called the threshold method to mitigate the undesired effects of embedding. Our results show that, within limited computational time, this threshold method improves QA's accuracy in solving the activity detection problem. Thus, this is promising to effectively reduce the negative impact of embedding.

In complement, [57] and [27] propose a new strategy based on Grover's quantum algorithm to perform the minimum searching so as to implement the ML receiver. As current quantum processors still suffer from noise in the so-called NISQ era, we propose to use Grover's routine with a reduced number of iterations but with several trials. We show that this approach presents a complexity advantage and allows to reach higher success probabilities than Grover's. This strategy may permit to timely deploy such AUD receiver even without perfect quantum devices.

8.2.2 Waveform and decoder design for massive random access

Participants: Maxime Guillaud, Anil Kumar, Sweta Suresh.

This research is related to challenge 2. Our first area of research builds upon multi-linear spreading as a joint modulation and coding technique adapted for massive random access. These results contribute to projects WARM-M2M and PERSEUS.

Our work has demonstrated that when using a multi-linear spreading modulation under Doppler distortion, each user's contribution remains a distinct rank-1 component in the tensorized received model, ensuring successful user separation. Hence we have proposed a post-CPD maximum likelihood Doppler estimator that can be implemented after user separation, avoiding an intractable joint estimation problem. The proposed sequential approach has moderate complexity and can achieve high accuracy with a limited amount of pilot symbols, making it particularly suitable for short-packet UMAC scenarios such as IoT and URLLC.

In another line of work, we have focused on the special case of multi-linear spreading with phase-shift keying (PSK) symbols. We have introduced a receiver/decoder algorithm which leverages the fact that PSK symbols are on the unit circle to relax the problem to the continuous domain; we propose a belief propagation (BP) message passing multi-user decoding algorithm, to jointly estimate the information bearing symbols and the channel coefficients. The messages (which are in general infinite-dimensional on the unit circle) are efficiently parameterized using the family of von Mises-Fisher directional distributions, yielding a compact representation with efficiently computable updates.

8.2.3 Spike Neural Networks for Wake Up radio

Participants: Claire Goursaud, Guillaume Marthe.

This work has been done in the context of the U-WAKE project, within the PhD of Guillaume Marthe [55, 56]. This is one of the core contribution of challenge 4, with contributions in the design of a specific PHY layer (challenge 3).

In the context of the Internet of Things (IoT), one of the greatest challenges lies in energy management. Wake-up Radios (WuR) enable devices to remain in standby mode while consuming minimal energy, activating only upon receiving specific signals. In this work, we propose the use of Spiking Neural Networks (SNNs) as Wake-up Radios (WuR). The neural network's role is to recognize the activation sequence of the targeted node within a bitstream to trigger its wake-up.

Our initial contribution demonstrates the relevance of these networks. Our second contribution involves the investigation and proposal of the Saturating Leaky Integrate and Fire (SLIF) model for WuR design. We proposed leveraging a bio-inspired phenomenon called Synaptic Interaction to create a temporal filter dependent on Inter-Spike Timing (IST) [25]. This model's parameters have been analyzed to understand how to adapt its IST ranges. The originality of this contribution lies in introducing a novel method for recognizing temporal sequences in the analog domain.

Subsequently, we explored various SLIF neural network topologies, including linear, diamond-shaped, and multilayer architectures, to understand how networks respond to spike sequences. We established foundational work for future research on neuromorphic networks in low-power IoT devices, particularly in WuRs.

Finally, in [34], in order to be able to detect the sequence in various channel conditions, we exploit the Spike-Timing Dependent Plasticity (STDP) learning rule to train the SNN. We show that the SNN succeeds in performing the sequence detection accurately, and delve into the training set design to improve the accuracy.

8.2.4 Optimization of Zero energy devices

Participants: Jean-Marie Gorce, Shanglin Yang.

Complementarily to the former task, and in the same context (low energy IoT applications) of challenge 4, we worked with Orange Labs (project 5G Event Labs and CIFRE), on the design of optimal code sequences for zero energy devices (ZED)[65]. This work concerns the design of new ultra-low power method for smartphones indoor localization, based on ZEDs beacons instead of active wireless beacons. Each ZED is equipped with a unique identification number coded into a bit-sequence, and its precise position on the map is recorded. An SM inside the building is assumed to have access to the map of ZEDs. The ZED backscatters ambient waves from base stations (BSs) of the cellular network. The SM detects the ZED message in the variations of the received ambient signal from the BS. We accurately simulate the ambient waves from a BS of Orange 4G commercial network, inside an existing large building covered with ZED beacons, thanks to a ray-tracing-based propagation simulation tool. Our first performance evaluation study shows that the proposed localization system enables us to determine in which room a SM is located, in a realistic and challenging propagation scenario. In 2025, we extended this work with the design of a Neyman-Pearson optimal detector, ensuring a given false alarm rate [39]. We then studied the performance of our detector from a theoretical point of view and by experimentation in CorteXlab [29]. These results open strong perspectives in the digital twin framework.

8.2.5 Channel charting

Participants: Maxime Guillaud, Yamil Vindas Yassine, Mohamed El Mehdi Makhlouf, Anil Kumar.

Channel charting (CC) is an unsupervised learning technique that utilizes channel state information (CSI) to construct a low-dimensional representation of the radio propagation environment through dimensionality reduction, with applications to predictive radio resource management and beam management, proximity detection, context awareness for digital twin applications, geofencing, and improving localization [49]. We investigate this topic within the CHIST-ERA CHASER project, and leverage CC for the purpose of sensing in project INSTINCT.

In 2025 we have explored two new approaches to make channel charting more robust:

1. Doppler-supervised channel charting, targeted to modulations such as OTFS for which the Doppler effect is estimated, is a weak form of supervision of the dimensionality reduction process aimed at making the channel chart closer to the physical reality by estimating the velocity through the Doppler effect [35];
2. Channel charting in the presence of reflective intelligent surfaces (RIS). RIS affect the electromagnetic channel and their effect is naturally captured by the charting process. When the RIS is antagonistic, we introduced a mechanism to adapt the training in order to minimize the channel chart disturbance due to the changing RIS state [37].

Furthermore, we have released the MOCSID dataset, a synthetic wireless propagation data designed for the purpose of benchmarking channel charting algorithms. It includes 10k realistic user trajectories in an outdoors campus environment, based on a 3D scene generated from OpenStreetMap data. In particular this dataset allows the benchmarking of distributed multi-site channel charting algorithms.

8.2.6 Additional contributions

The following references are indicated in our publication list but are not detailed in this report.

- The work in [30] is related to the PhD of Yamil Vindas, done before he joined the team.
- The work in [45] is the scientific report of the PEPR project PERSEUS to which MARACAS is contributing.

9 Bilateral contracts and grants with industry

9.1 Bilateral contracts with industry

Participants: Malcolm Egan, Jean-Marie Gorce.

We have currently involved in the following partnerships:

1. Inria-Nokia Bell Labs common lab : Jean-Marie Gorce (until march 2025), then Malcolm Egan, lead the challenge Learnnet [2024-2028].
2. Challenge FedMalin : Jean-Marie Gorce, Malcolm Egan and Tan Khiem Huynh are involved in this challenge.

9.2 Bilateral grants with industry

Participants: Fabrice Dupuy, Malcolm Egan, Jean-Marie Gorce, Claire Goursaud, Claire Mesny, Shanglin Yang.

1. CIFRE with Orange Labs (2022-2025) on passive TAG aided localization with zero-energy-devices anchors. This work is adressed by Mr Shanglin Yang (PhD student), defended in Dec 2025. He is co-supervised by Jean-Marie Gorce and Guillaume Villemaud from the team Rhodes, CITI. The objective was to design an optimal code for a passive TAG, with its optimal detector (in Bayesian sens). The proposed solution has been demonstrated in SLICES/CorteXlab.

2. CIFRE with Orange Labs (2022-2025) on quantum algorithms for networks. This project is developed in the PhD of Fabrice Dupuy. The aim of the funded thesis was to pave the way for building a quantum network. The objective was to determine which protocols and algorithms are suitable for the quantum network (i.e. when the transmitted data is quantum), depending on the repeaters and links performances. The thesis had to be stopped due to the student health issues, but has been renewed with a new student (Claire MESNY, PhD starting end of 2024).

3. SPIE ICS Chaire (2022-2025) - 2nd phase: A funded postdoc studied communication strategies to support predictive maintenance systems. A funded PhD (in collaboration with Dynamid and Agora) is currently investigating energy efficient training strategies for DNNs.

10 Partnerships and cooperations

10.1 International initiatives

10.1.1 AI-HEAL Associate team with ABV-IIITM, Gwalior, India

Participants: Maxime Guillaud (Inria), Mahendra Kumar Shukla (ABV-IIITM) , Jean-Marie Gorce (Inria), Om Jee Pandey (Indian Institute of Technology - BHU, Varanasi, India), Aditya Trivedi (ABV-IIITM), Anjali (ABV-IIITM) , Anil Kumar (Inria) .

This associate team, a collaboration between Inria and Atal Bihari Vajpayee-Indian Institute of Information Technology and Management (ABV-IIITM) in Gwalior, India is dedicated to developing advanced signal processing techniques driven by artificial intelligence (AI) to ensure the security and integrity of healthcare data and enhance the overall performance and reliability of wireless communications in healthcare systems. Publications: in [28] we have studied how friendly jamming can be leveraged to disrupt eavesdroppers in the contact of the Gaussian multiple-access wiretap channel.

10.2 International research visitors

10.2.1 Visits of international scientists

Visiting researcher: Pratyush Pranav

Partner Institution(s):
- Bennett University, India

June 2025, 1 week

Visiting researcher: Mayank Garg

Partner Institution(s):
- Ashoka University, India

November 2025, 2 days

Visiting researcher: Andrea Benso

Partner Institution(s):
- University of Florence, Italy

July 2025, 1 week

10.3 European initiatives

10.3.1 Horizon Europe

INSTINCT

Participants: Maxime Guillaud, Jean-Marie Gorce, Claire Goursaud, Cyrille Morin, Leonardo Sampaio, Anil Kumar, Mohamed El Mehdi Makhlouf.

INSTINCT project on cordis.europa.eu

Title: Joint Sensing and Communications for Future Interactive, Immersive, and Intelligent Connectivity Beyond Communications

Duration: From January 1, 2024 to December 31, 2026

Partners: Partners: Barkhausen Institute, University of Piraeus, BOSCH, Aalto University, Fraunhofer, Greenerwave, NEC Labs Europe, i2CAT, Internet i Innovacio Digital a Catalunya, University of Oulu, CentraleSupelec, Telefonica

Inria contact: Maxime Guillaud

Coordinator: Barkhausen Institute

Summary: The INSTINCT project is going to enable globally sustainable, interactive, immersive, and intelligent 'beyond communications' 6G connectivity by developing three complementary but critical breakthrough technology pillars:

- sensing-assisted communication technologies, thus allowing localization, tracking, mapping, monitoring, imaging, incident detection and semantics become integral parts of connectivity services (Pillar 1),
- intelligent surfaces, holographic radios and cell free systems, which offer wavefront engineering functionalities and tuneability of the wireless environment and can act as reconfigurable and intelligent sensors (Pillar 2), and
- Machine Learning (ML) techniques-based co-design of Sensing and Communications

INSTINCT proposes a revolutionary path to 6G and has the ambition to specify the relevant KPIs/KVIs, formulate suitable models, devise the theoretical framework, invent new technologies, evaluate via simulations and validate by means of 2 HW and 1 SW demonstrators, a networked intelligence concept able to meet the unprecedented 6G requirements. To realise this vision, INSTINCT consortium brings together all relevant stakeholders from across Europe, with an impressive record of interdisciplinary research excellence, technology innovation, standardisation and transfer, and implementation expertise.

CHASER Channel Charting as a Service (2023-2026), CHIST-ERA

Participants: Maxime Guillaud, Anil Kumar, Mohamed El Mehdi Makhlouf.

CHASER is a project set up under the CHIST-ERA Horizon Europe initiative, and funded by the French, Swiss and Finnish research agencies. The project focuses on making channel charting a practical tool in future radio access networks. By applying dimensionality reduction to channel state information, channel charting produces a pseudo-location with no recourse to classical positioning methods, potentially opening up a range of location-based applications with significantly reduced overhead. The objective of CHASER is to develop methods and algorithms allowing to implement network-wide CC, and to develop its predictive capabilities when applied to real-world use cases involving multiple base stations or access points, heterogeneous users and dynamically changing environments, with the ultimate goals of developing CC into a robust and versatile pseudo-positioning method to assists a number of network functions and user-level applications.

- Website: https://chaser-project.github.io/
- People involved: Maxime Guillaud, Mohamed el Mehdi Makhlouf, Yamil Vindas, Anil Kumar
- Partners: ETH Zürich, Aalto University, University of Minho

10.3.2 H2020 projects

TESTBED2

Participants: Malcolm Egan.

TESTBED2 project on cordis.europa.eu

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

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

Partners:

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

Inria contact: Samir PERLAZA

Coordinator: University of Durham

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

10.4 National initiatives

10.4.1 Inria incentive actions

FedMalin challenge (2022-2026)

Participants: Malcolm Egan, Jean-Marie Gorce, Tan Khiem Huynh.

FedMalin is a research project that spans 11 Inria research teams and aims to push FL research and concrete use-cases through a multidisciplinary consortium involving expertise in ML, distributed systems, privacy and security, networks, and medicine. We propose to address a number of challenges that arise when FL is deployed over the Internet, including privacy, fairness, energy consumption, personalization, and location/time dependencies.

LearnNet challenge (2024-2028)

Participants: Malcolm Egan, Jean-Marie Gorce, Loukas Duque.

This challenge lead by MARACAS involves 7 other teams with a deep background either in network and communications, or in statistics and data science. The Learning Networks framework is proposed as a new paradigm to explore novel research avenues at the crossroads of networking and machine learning. The objective is twofold: to revolutionize the design of network protocols in the view of machine learning applications, and to explore the use of machine learning to improve network management itself. Heterogeneity is a central question in this project since future learning networks will have to operate heterogeneous systems.

10.4.2 ANR

ANR WARM-M2M

Title: Waveforms and Resource Management for M2M over large areas

Duration: From 2024 to 2028

Partners: University of Southern Brittany, Thales, Nokia Bell-Labs

Inria contact: Maxime Guillaud

Coordinator: University of Southern Brittany

Summary: The objective of the WARM-M2M project is to develop novel physical layer (waveforms, channel codes) and medium access control, radio access protocols and distributed coordination mechanisms for massive M2M scenarios allowing multiple low earth orbit satellites to jointly serve a massive number of nodes with sporadic IoT traffic, under controlled reliability and/or latency constraints, achieving a high area spectral efficiency at the network scale, with limited device complexity and protocol overhead.

People involved: Jean-Marie Gorce, Maxime Guillaud, Kassem Saied, Samya Tannir, Malcolm Egan

JCJC TCDTP

Title: Tailoring Communications in Multi-Tier Computation for Digital Twinned Process Control

Duration: From 2024 to 2027

Partners:

- CITI Laboratory
- INSA Lyon
- Inria

Inria contact: Malcolm Egan

Coordinator: Inria

Summary: TCDTP is concerned with the development of digital twin based process control within multi-tier computation architectures from the perspective of communications. Aligned with the goal-oriented perspective, the project aims to jointly design compression, resource allocation, and learning in order to ensure efficient stabilization of physical processes.

People involved: Malcolm Egan, Sih-Yu Chou, Khiem Huynh, Oussama Harrak

Related publications: [48, 24, 32]

10.4.3 Research projects in the framework of Programme Agencies

Participants: Malcolm Egan, Jean-Marie Gorce, Claire Goursaud, Maxime Guillaud, Leonardo Sampaio, Matthieu Imbert, Cyrille Morin.

Within the national *Priority Research Programme and Equipment* (PEPR) programme, we are involved in multiple sub-projects of the “Future Networks” PEPR (PEPR-NF), which is affiliated to the program agency “From components to systems and digital infrastructure”, led by CEA. Telecommunication networks represent a key issue for French and European industry, society and digital sovereignty. The French government launched a dedicated national strategy, with the ambition to produce significant public research efforts so the national scientific community contributes fully to making progress that clearly responds to the challenges of 5G and beyond. In this context, the CNRS, the CEA and the Institut Mines-Télécom (IMT) are co-leading the ’5G’ acceleration PEPR to support upstream research into the development of advanced technologies for 5G+. MARACAS contributes to:

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

FOUND - PEPR Future Networks MARACAS, with MATHSNET and NEO, contributes to FOUNDS. The project organizes fundamental research in the following directions: The study of the fundamental theoretical limits in the sense of physics and information theory, with many open questions linked to the use of the spatial dimension, strong latency constraints or even the taking into account of the signification of what is transmitted from coding, protocols and up to the physical layer. The determination of the optimal spatial organization of the network elements, taking into account the limitations of information theory. This will require new mathematical tools and models, which will be key elements of this project. The design of real-time and non-real-time distributed control algorithms to exploit such network architectures. The main objective here is to get closer to the fundamental limits studied in this project.

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

11 Dissemination

11.1 Promoting scientific activities

11.1.1 Scientific events: organisation

- Maxime Guillaud organized the CHASER Workshop on Privacy in Wireless Communications.

11.1.2 Scientific events: selection

Chair of conference program committees

- Malcolm Egan: TPC Chair ACM NanoCom 2026
- Malcolm Egan: TPC Chair Workshop on Molecular Communications 2026

Member of the conference program committees

- Malcolm Egan: IEEE ICC 2025, IEEE GLOBECOM 2025, NeurIPS 2025, ACM NanoCom 2025
- Claire Goursaud: IEEE GLOBECOM QCIT 2025, WF-IoT 2025
- Kevin Zagalo: RTCSA 2025
- Leonardo Cardoso: IEEE ICC 2025, IEEE ICMLCN 2025, WCNC 2025, WCNC 2026

Reviewer

- Malcolm Egan: IEEE ISIT 2025
- Claire Goursaud: Asilomar 2025
- Kevin Zagalo: WCNC 2026
- Leonardo Cardoso: IEEE ICC 2025, IEEE ICMLCN 2025, WCNC 2025, WCNC 2026
- Maxime Guillaud: International Joint Conference on Neural Networks (IJCNN), IEEE GLOBECOM 2025, IEEE WCNC 2026, IEEE International Conference on Machine Learning for Communication and Networking (ICMLCN) 2025, International Symposium on Topics in Coding (ISTC) 2025, IEEE Globecom 2025 Workshop on Emerging Topics in 6G Communications, Asilomar 2025
- Cyrille Morin: WCNC 2026

11.1.3 Journal

Member of the editorial boards

- Malcolm Egan: Nature Scientific Reports
- Maxime Guillaud: IEEE Transactions on Wireless Communications
- Claire Goursaud: Transactions on Emerging Telecommunications Technologies, Internet Technology Letters

Reviewer - reviewing activities

- Claire Goursaud: IEEE IoT magazine
- Maxime Guillaud: Journal of Selected Topics in Signal Processing, IEEE Transactions on Wireless Communications, IEEE Transactions on Information Theory, IEEE Wireless Communications Magazine,
- Malcolm Egan: IEEE Transactions on Machine Learning in Communications and Networking, The Journal of Physical Chemistry Letters, IEEE Transactions on Molecular, Biological, and Multi-Scale Communications
- Leonardo Cardoso: IEEE Transactions on Communications

11.1.4 Invited talks

- Malcolm Egan
  - LMBP-ISM Joint Workshop 2025, Clermont-Ferrand
- Maxime Guillaud
  - Tutorial at the IEEE International Conference on Machine Learning for Communication and Networking, Barcelona, Spain, May 26, 2025
  - PEPR Future Networks PC9 Workshop, Bordeaux, June 3, 2025
  - France-Japan (Inria/NICT) Joint Workshop, Sophia-Antipolis, France, July 04, 2025
  - University of Southern California, Los Angeles, CA, October 30, 2025
  - IEEE ComSoc School Series Andhra Pradesh (online), December 10, 2025
- Kevin Zagalo
  - The Way to 6G Workshop, IEEE MASCOTS, October 23, 2025.
  - Journées PEPR Réseaux du futur, Bordeaux, June 2, 2025.
- Jean-Marie Gorce
  - Invited talk at the 21st ICDCIT 2025 conference, Bubaneshwar, India, 8-11, January, 2025.
  - Tutorial at the Training event Network and AI - Thursday, 23rd of October 2025, Paris.

11.1.5 Scientific expertise

- Maxime Guillaud is a member of the technical experts group on mobile radio networks of ARCEP, the French telecommunications regulatory authority, since 2023.
- Claire Goursaud was a member of the ANR CE48 evaluation committee.
- Maxime Guillaud was a member of the ANR CE25 evaluation committee.

11.1.6 Research administration

- Malcolm Egan:
  - COMI Lyon,
  - Responsible Lyon Mission Jeune Chercheur (MJC),
  - Jury MCF ENSEA,
  - External Evaluator School of AI Bennett University.
- Maxime Guillaud
  - Steering committee of the CNRS Information, Learning, Signal, Image and ViSion research group (GdR IASIS).
- Claire Goursaud
  - Deputy director of CITI Lab.
  - CNU 61 member.
- Jean-Marie Gorce
  - Head of Research (since May, 2025), Directorate-General for Science, Inria

11.2 Teaching - Supervision - Juries - Educational and pedagogical outreach

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

- Bachelor : L Cardoso - Electromagnetism and Wave Physics, 104 eqTD, L2, First Cycle Dept, INSA Lyon, France.
- Bachelor : L Cardoso - Mathematics for Engineering, 60h eqTD, L1, First Cycle Dept, INSA Lyon, France.
- Bachelor : L Cardoso, C Goursaud, K. Zagalo - 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 : K. Zagalo, JM Gorce (until April 25) - Advanced Digital Communications, 64h eqTD, M1, Telecommunications dept, INSA Lyon, France.
- Master : K. Zagalo - Networks Performance Evaluation, 14h eqTD, M1, Telecommunications dept, INSA Lyon, France.
- Master : L Cardoso, K Zagalo - Radio Access Networks, 32h eqTD, M1, Telecommunications dept, INSA Lyon, France.
- Master : C Goursaud - Communications Systems, 32h eqTD, M1, Telecommunication
- Master : C Goursaud - Quantum Algorithms Projects, 32h eqTD, M2, Telecommunications dept, INSA Lyon, France.

Maracas members (M Guillaud, C Goursaud, C Morin) also gave a 3 days teaching course for industrial professionals on wireless systems planification.

11.2.1 Supervision

- Romain PIRON defended his PhD thesis “Quantum Algorithms for NOMA Systems” on October 16th, 2025.
- Shanglin YANG defended his PhD thesis “Spatio-temporal Synchronization and Signal Processing for Zero-Energy Digital Twins in Ambient Backscatter Communication Systems” on 28 November 2025.

11.2.2 Juries

- Malcolm Egan:
  - A. Benso University of Florence, Italy (Reporter)
  - A. Upadhyay Bennett University, India (Reporter)
  - C. Bouette ENSEA, France (Examiner)
- Maxime Guillaud
  - PhD committee of Mohsen Ahadi (Eurecom, Reporter)
  - PhD committee of Dian Echevarria (University of Oulu, Finland, Reporter)
  - PhD committee of Romain Piron (INSA Lyon, Examiner)
  - PhD committee of Wissal Benzine (Eurecom, Examiner)
  - Hiring committee Telecom Paris
  - Hiring committee Inria Lyon Center
- Claire Goursaud
  - PhD committee of Timothé PRESLES (Université de Bretagne Occidentale, Reporter)
  - Hiring committee INSA Lyon
  - Hiring committee Centrale Supélec
  - Hiring committee INSA Rennes
- Jean-Marie Gorce
  - PhD committee of Arthur Michon (Université de Toulouse, Reviewer)
  - PhD committee of Diane Orhan (Université de Bordeau, Examiner)
  - HdR committee of Robin Gerzaguet (Université de rennes, Reviewer)

11.2.3 Educational and pedagogical outreach

Claire Goursaud

- Conference on quantum algorithm in a preparatory school (Jean Perrin, Lyon)
- Chiche at Lycée Aux Lazaristes (Lyon)

11.3 Popularization

11.3.1 Participation in Live events

- Claire Goursaud organized the CITI laboratory’s interventions during the Fête de la science.
- Cyrille Morin held a stand with a GNU Radio spectrum monitoring demonstration in FOSDEM 2025 (Bruxelles), showcasing both RF spectrum usage and the use of free software in research.
- Cyrille Morin held a stand in EuCNC 2025 (Poznan) with a live remote demonstration of Reflective Intelligent Surface (RIS) optimization of path loss inside of the CorteXlab Platform, with a similar live demonstration at the 2025 SLICES-FR summer school.

12 Scientific production

12.1 Major publications

[1] B. C. Akdeniz, M. Egan and B. Q. Tang. 'Equilibrium Signaling: Molecular Communication Robust to Geometry Uncertainties'. In: *IEEE Transactions on Communications* 69.2 (Feb. 2020), pp. 752–765. DOI: 10.1109/TCOMM.2020.3034662. URL: https://hal.science/hal-03018278.

[2] 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 (cit. on p. 10).

[3] M. De Freitas, M. Egan, L. Clavier, A. Goupil, G. W. Peters and N. Azzaoui. 'Capacity Bounds for Additive Symmetric α -Stable Noise Channels'. In: *IEEE Transactions on Information Theory* 63.8 (Aug. 2017), pp. 5115–5123. DOI: 10.1109/TIT.2017.2676104. URL: https://hal.univ-reims.fr/hal-02088563.

[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.

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[9] P. Ferrand, M. Guillaud, C. Studer and O. Tirkkonen. 'Wireless Channel Charting: Theory, Practice, and Applications'. In: *IEEE Communications Magazine* (2023). DOI: 10.1109/MCOM.001.2200344. URL: https://inria.hal.science/hal-04067052.

[10] 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) (cit. on p. 10).

[11] J.-M. Gorce, Y. Fadlallah, J.-M. Kelif, H. V. Poor and A. Gati. 'Fundamental limits of a dense iot cell in the uplink'. In: *Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt), 2017 15th International Symposium on*. IEEE. 2017, pp. 1–6.

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12.2 Publications of the year

International journals

[22] A. Bardou, J.-M. Gorce and T. Begin. 'Assessing the Performance of NOMA in a Multi-Cell Context: A General Evaluation Framework'. In: *IEEE Transactions on Wireless Communications* 25 (11th July 2025), pp. 415–428. DOI: 10.1109/TWC.2025.3584178. URL: https://hal.science/hal-05474246 (cit. on p. 18).

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[25] G. Marthe, C. Goursaud and L. Clavier. 'Using Synapse Saturation in Spiking Neural Networks for Wake Up Receivers in Internet of Things Networks'. In: *IEEE Internet of Things Journal* (2025), pp. 1–1. DOI: 10.1109/JIOT.2025.3599668. URL: https://hal.science/hal-05229337 (cit. on p. 20).

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International peer-reviewed conferences

[30] M. Dupouy, Y. Vindas, M. Almar, B. K. Guépié and P. Delachartre. ‘Weakly-Supervised Semantic Space Structuring: Cardiac Cycle Position For Cerebral Emboli Visualization Using Contrastive Learning’. In: *2025 IEEE International Symposium on Biomedical Imaging (ISBI)*. 2025 IEEE International Symposium on Biomedical Imaging (ISBI). Houston, United States, 2025. DOI: 10.1109/ISBI60581.2025.10981113. URL: https://hal.science/hal-04922841 (cit. on p. 21).

[31] M. Dupouy, Y. Vindas, T. Dambry, B. K. Guépié and P. Delachartre. ‘RgeoJSD: Robust Geometric Jensen-Shannon Divergence Noise-Tolerant Loss for Cerebral Emboli Classification’. In: *2025 IEEE International Ultrasonics Symposium (IUS)*. 2025 IEEE International Ultrasonics Symposium (IUS). Utrecht, Netherlands: IEEE, 20th Oct. 2025, pp. 1–4. DOI: 10.1109/IUS62464.2025.11201339. URL: https://hal.science/hal-05234901.

[32] M. Egan. ‘Risk-Aware Estimation From Compressed Data Beyond the Bayes Risk’. In: IEEE International Symposium on Information Theory - ISIT 2025. Ann Arbor, United States, 22nd June 2025. URL: https://hal.science/hal-05037552 (cit. on pp. 13, 18, 26).

[33] T.-K. Huynh, M. Egan, G. Neglia and J.-M. Gorce. ‘Streaming Federated Learning with Markovian Data’. In: NeurIPS 2025 - Thirty-Ninth Annual Conference on Neural Information Processing Systems. San Diego, United States, 2nd Dec. 2025. URL: https://inria.hal.science/hal-05422204 (cit. on pp. 13, 17).

[34] P. Joseph, G. Marthe and C. Goursaud. ‘STDP Training Design and Performances of a SNN for Sequence Detection as a Wake Up Radio in a IoT Network’. In: WCNC 2025 - IEEE Wireless Communications and Networking Conference. Milan, Italy: IEEE, 2025, pp. 1–6. DOI: 10.1109/WCNC61545.2025.10978731. URL: https://hal.science/hal-05372664 (cit. on p. 20).

[35] A. Kumar, Y. Vindas Yassine and M. Guillaud. ‘Doppler-Supervised Channel Charting’. In: ICC 2026 - IEEE International Conference on Communications. Glasgow, United Kingdom, 24th May 2026. URL: https://hal.science/hal-05395262 (cit. on pp. 13, 21).

[36] M. E. M. Makhlouf, M. Guillaud and Y. Vindas Yassine. ‘Multi-cell Outdoor Channel State Information Dataset (MOCSID)’. In: *AI4C – AI/ML Solutions for Communications*. The 2025 European Conference on Networks and Communications (EuCNC) & 6G Summit. Pozan, Poland, 3rd June 2025. URL: https://hal.science/hal-05037063 (cit. on p. 13).

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Conferences without proceedings

[40] K. Saied and M. Guillaud. 'Doppler Frequency Estimation in Tensor-Based Modulation via Post-CPD Maximum Likelihood'. In: WCNC 2026 - IEEE Wireless Communications and Networking Conference. Kuala Lumpur, Malaysia, 13th Apr. 2026. URL: https://hal.science/hal-05470265.

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Edition (books, proceedings, special issue of a journal)

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Reports & preprints

[43] O. Harrak, M. Egan, C. Goursaud, M. L. Alberi Morel and A. Conte. *Bias Mitigation for Federated Learning with Spatially Correlated Participation*. 2025. URL: https://hal.science/hal-05265910.

Other scientific publications

[44] M. Dupouy, Y. Vindas, M. Almar, B. K. Guépié and P. Delachartre. 'Comparaison de Méthodes d'Apprentissage pour l'Annotation Semi-Automatique Multi-labels des Micro-Emboles'. In: IABM. Nice, France, 17th Mar. 2025. URL: https://hal.science/hal-05484775.

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