UMR IRISA

# Activity Report 2025

## Team ERMINE

Measuring and Managing Network Operation and Economics

*Joint team with Centre Inria de l'Université de Rennes*

D2 – Networks, Telecommunications and Services

Université de Rennes | rennes | INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES RENNES | cnrs | Inria | Inserm | CentraleSupélec | IMT Atlantique Bretagne-Pays de la Loire École Mines-Télécom | Université Bretagne Sud ubs

# Project-Team ERMINE

*Creation of the Project-Team: 2022 June 01*

## Keywords

**Computer sciences and digital sciences**

A1.2.1. – Dynamic reconfiguration
A1.2.2. – Supervision
A1.2.4. – QoS, performance evaluation
A1.2.6. – Sensor networks
A1.3.3. – Blockchain
A1.3.4. – Peer to peer
A1.3.5. – Cloud
A1.3.6. – Fog, Edge
A1.6. – Green Computing
A6.1.2. – Stochastic Modeling
A6.2.3. – Probabilistic methods
A6.2.4. – Statistical methods
A6.2.6. – Optimization
A8.2.1. – Operations research
A8.6. – Information theory
A8.7. – Graph theory
A8.8. – Network science
A8.9. – Performance evaluation
A8.11. – Game Theory
A9.2. – Machine learning
A9.2.1. – Supervised learning
A9.2.2. – Unsupervised learning
A9.2.3. – Reinforcement learning
A9.2.6. – Neural networks
A9.2.8. – Deep learning
A9.7. – AI algorithmics
A9.9. – Distributed AI, Multi-agent

## Other research topics and application domains

B6.2.1. – Wired networks

B6.2.2. – wireless networks

B6.3.2. – Network protocols

B6.3.3. – Network Management

B6.3.5. – Search engines

B6.4. – Internet of things

B9.6.3. – Economy, Finance

# Contents

**Project-Team ERMINE** **1**

**1 Team members, visitors, external collaborators** **5**

**2 Overall objectives** **6**

**3 Research program** **6**
3.1 Context . . . 6
3.2 Managing network operations . . . 7
3.3 Measuring . . . 8
3.4 Research axes . . . 9

**4 Application domains** **10**

**5 Social and environmental responsibility** **10**
5.1 Impact of research results . . . 10

**6 Highlights of the year** **11**
6.1 Awards . . . 11

**7 Latest software developments, platforms, open data** **11**
7.1 Latest software developments . . . 11
7.1.1 SNIDE . . . 11
7.1.2 DemoWehe . . . 11

**8 New results** **12**
8.1 Network Economics . . . 12
8.2 Managing next generation networks & massive IoT communication . . . 13
8.3 Measuring, monitoring & regulation . . . 14
8.4 Measuring performance metrics based on models . . . 15
8.5 Artificial Intelligence (AI) in networking . . . 17

**9 Bilateral contracts and grants with industry** **19**
9.1 Bilateral contracts with industry . . . 19
9.1.1 DEFI SmartNet . . . 19
9.1.2 ANR Genie . . . 20
9.1.3 ANR EDEN4SG . . . 20
9.2 Bilateral Grants with Industry . . . 21
9.2.1 CRE on SCHC with Orange . . . 21
9.2.2 Sustainable AI Integration in 6G Networks: Energy Efficiency and Environmental Impact Optimization . . . 21
9.2.3 Cifre on safe resource management in 6G with distributed decision making . . . 21
9.2.4 Cifre on societal, environmental, and economic impacts of digital infrastructures . . . 22
9.2.5 Cifre on green video streaming: modeling, evaluation and regulation . . . 22
9.2.6 Contract with InterDigital "UX-Centric Adaptation of Multi-User Real-Time XR Applications Over Wireless Network" . . . 22

**10 Partnerships and cooperations** **22**
10.1 International initiatives . . . 22
10.1.1 Associate Teams in the framework of an Inria International Lab or in the framework of an Inria International Program . . . 22
10.2 International research visitors . . . 23
10.2.1 Visits of international scientists . . . 23
10.3 National initiatives . . . 25

10.3.1 PEPR 5G and future networks . . . 25
10.3.2 Inria pilot-project REGALIA . . . 25
10.4 Regional initiatives . . . 25
10.4.1 Informal local partners . . . 25

**11 Dissemination** **25**
11.1 Promoting scientific activities . . . 25
11.1.1 Scientific events: organisation . . . 25
11.1.2 Journal . . . 27
11.1.3 Invited talks . . . 27
11.1.4 Leadership within the scientific community . . . 27
11.2 Teaching - Supervision - Juries - Educational and pedagogical outreach . . . 27
11.2.1 Teaching . . . 27
11.2.2 Supervision . . . 29
11.2.3 Juries . . . 30

**12 Scientific production** **30**
12.1 Publications of the year . . . 30

# 1 Team members, visitors, external collaborators

## Research Scientists

- Bruno Tuffin [Team leader, INRIA, Senior Researcher, HDR]
- Mael Le Treust [CNRS, Researcher]
- Gerardo Rubino [INRIA, Emeritus, HDR]
- Bruno Sericola [INRIA, Senior Researcher, HDR]
- Chetna Singhal [INRIA, Researcher, from Oct 2025]

## Faculty Members

- Soraya Ait Chellouche [UNIV RENNES]
- Mouloud Atmani [UNIV RENNES]
- Yassine Hadjadj-Aoul [UNIV RENNES, Professor, HDR]
- Sofiene Jelassi [UNIV RENNES, Associate Professor]
- Patrick Maillé [IMT ATLANTIQUE, Professor, HDR]
- Raymond Marie [UNIV RENNES, Emeritus, HDR]
- Cesar Viho [UNIV RENNES, HDR]

## Post-Doctoral Fellow

- Olivier Massicot [CNRS, Post-Doctoral Fellow, from Sep 2025]

## PhD Students

- Etienne Faivre D'Arcier [INTERDIGITAL, CIFRE]
- Burak Kara [SYNAMEDIA, CIFRE]
- Benedicte Kongo [Orange, CIFRE]
- Wilem Lamdani [UNIV RENNES]
- Parsa Rajabzadeh [NOKIA BELL LAB, CIFRE]
- Orland-Medy Saizonou [INRIA]
- Lucas Taucoory [NOKIA, CIFRE, from Apr 2025]
- Hyun Joon Yoo [UNIV RENNES, from Dec 2025]

## Technical Staff

- Nada Dandachi [INRIA, Engineer, until May 2025]
- Ivan Martinez Bolivar [UNIV RENNES, until Oct 2025]
- Chetna Singhal [INRIA, Engineer, until Sep 2025]

### Interns and Apprentices

- Youcef Benali [INRIA, Intern, from Feb 2025 until Jul 2025]
- Diego Carreaux [ECOLE POLY PALAISEAU, Intern, from Jul 2025 until Aug 2025]
- Maëlys Eymond [ENSTA, Intern, from Mar 2025 until Aug 2025]
- Kilian Le Saux [INRIA, Intern, from Apr 2025 until Aug 2025]

### Administrative Assistant

- Gwenaelle Lannec [UNIV RENNES]

### Visiting Scientists

- Jörn Altmann [Seoul National University, from Oct 2025 until Oct 2025]
- Hector Cancela [Universidad de la República, Uruguay, from Apr 2025 until Apr 2025]
- Eunice Fuentes Juarez [IPN MEXICO, from Mar 2025 until Apr 2025]
- Pierre L'Ecuyer [UNIV Montréal, from Apr 2025 until Apr 2025]
- Fatima Zahra Mardi [UNIV Moulay Ismail, from Apr 2025 until Jul 2025]
- Marvin Nakayama [New Jersey Institute of Technology, from May 2025 until May 2025]
- Yijie Peng [Peking University, until Jan 2025]

# 2 Overall objectives

Networks are omnipresent and increasingly complex, and require an efficient management of their operations. The ERMINE team designs and analyzes procedures and policies for efficiently managing network operations, but also works on the required measurement and monitoring of performance metrics. Our specific and original management activity focuses on network economics, regulation, and automated decision making. In terms of needed measurement, we make use of standard modeling and performance analysis techniques, but also carry out direct measurements to be analyzed statistically. A cross-cutting research axis for both management and measuring is artificial intelligence. Our activity is a trade-off between methodological/mathematical developments and practical implementations.

# 3 Research program

## 3.1 Context

Telecommunication networks are ubiquitous in our daily life. The network ecosystem and its infrastructure are increasingly complex with more and more involved actors and technologies which have to interoperate. This complexity is illustrated in Figure 3.1, where the basic network paradigm with network operators simply sending content from/to end users has moved to a topology with many players having different roles. A complete telecommunications system has to integrate traditional networks capabilities but also all other innovative Internet services into a single service platform. Selfishness of actors, heterogeneity of requests and technologies, interoperability of services and automation of decisions are major challenges to be tackled.

ERMINE deals with network operations management and the required associated monitoring and measurements and performance analysis. Operation network management means for us performance-based management, fault analysis, or the design of procedures and strategies for resource provisioning and quality-of-service fulfillment. On this management side, we aim at looking at the whole topic of networks economics, studying the best economic strategies of actors of the digital economy, their interactions and the potential need

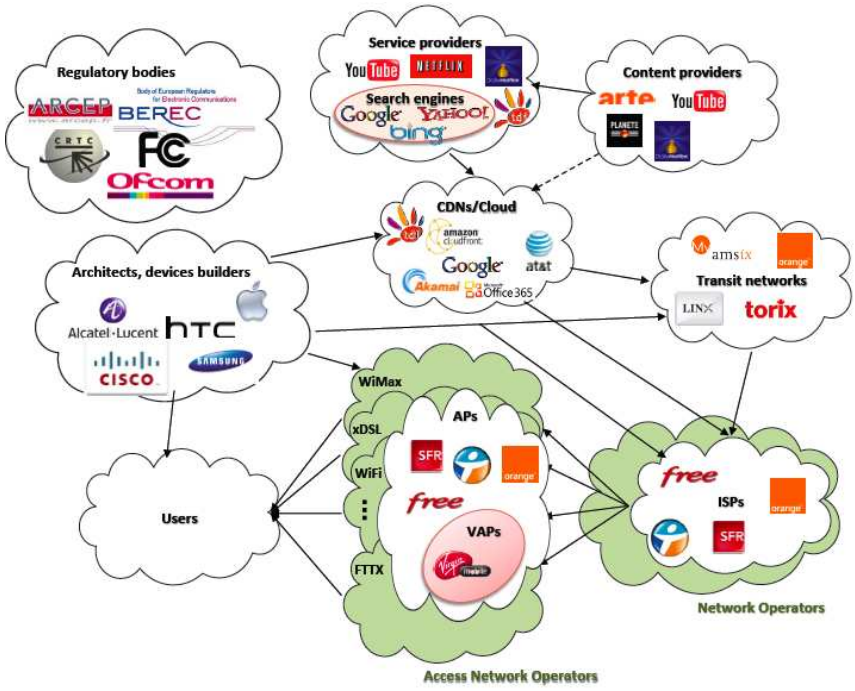



Figure 1: The ICT ecosystem: a complex set of interdependent actors

for regulation. We also want to address resource management through artificial intelligence for automated decision as another main research direction. On the measurement side, monitoring services of all sorts is a major challenge for regulatory bodies to ensure a fair and legal behavior of providers, and is also of primary importance for providers themselves to optimize decisions; this often requires new modeling, analysis and artificial intelligence tools. This is detailed below.

## 3.2 Managing network operations

The heterogeneity and complexity of the ICT (for Information & Communications Technology) world bring a number of challenges to network operations management. ERMINE addresses key issues for network management: i) the challenges of ICT economics; ii) network control and interoperability iii) automated decisions through AI.

ICT is omnipresent in our modern society, and the economy has gone beyond the industrial economy to the Internet and ICT economy. Thanks to hyper-connectivity, there are now lots of opportunities for innovation. As of May 2020, among the top-10 most valuable companies worldwide, seven are ICT companies, trusting the places from 2 to 8 (Microsoft, Apple Inc., Amazon Inc., Alphabet Inc., Facebook, Alibaba Group, Tencent). Internet Service Providers (ISPs), Content Delivery Networks (CDNs) and cloud providers, social network actors, all services and content providers are among actors needing a business model as profitable as possible. Designing and analyzing such business models and their acceptance by end users are issues to be addressed, leading to challenges in terms of outcome for all players (who act in most cases selfishly) and in terms of benefits for society. On that last point, regulators have to determine rules that actors need to follow in order to avoid harmful behaviors and maximize social welfare. The issues we address include: the design of economic rules for new services, the analysis of the impact of players decisions and interactions, and the potential design of rules or incentives from regulatory bodies leading to the most adequate (social) outcome. One of the frameworks to be used is that of game theory, and in particular of mechanism design.

There has been a metamorphosis in the last few years on the management of network operations, driven by the virtualization of networks and services. This evolution allows to meet the needs in terms of the dynamic scaling of infrastructures and the agility of the decision-making, namely, a necessary prerequisite for reducing operating costs as well as improving return on investment. These developments are radically changing the

way services are managed, as they become more complex (i.e., services in the form of graphs, micro-services, etc.), their expectations can be very diverse and strategies for their placement could consider a single domain or spanning across several domains, whether cooperative or not. Thus, the operation of the network becomes extremely difficult and requires not only optimization of resources but also economic considerations, especially when management involves several domains. We believe that *automated* management and control is the key direction for an efficient solution. We deal with the automation of the network by contributing to ongoing standardization efforts, notably by the "Zero touch network & Service Management" (ZSM) group of the ETSI (the European Telecommunications Standards Institute), and through the elaboration of solutions based on the most recent advances in machine learning techniques, and in particular in deep reinforcement learning. Some of the challenges we tackle include dynamic placement of complex and constrained – QoS/QoE – services (i.e., network slicing), automatic service scaling, congestion control in the context of new generation networks, including IoT networks (e.g., massive Machine-Type Communications (mMTC)). Different aspects are taken into account when developing the various solutions, including reliability, resilience, guaranteed performance (i.e., deterministic networks), but also the energy efficiency on which the viability of the latter depends. Ensuring the performance of the solutions when using machine learning techniques is, however, a major problem that is poorly addressed in the literature. We address it by proposing techniques that offer at least similar performances to heuristics. Indeed, even if heuristics can be very efficient, they often have, however, some limitations. One of these is the blocking at the level of local minima. AI techniques can address this issue encountered in combinatorial problems (of the NP-hard type, such as the travelling salesman one). They sometimes yield near-optimal results. AI techniques have the additional advantage of being able to learn by interacting with the environment, and can therefore find solutions that heuristics could not.

## 3.3 Measuring

A proper management of network services and operations cannot be effective without measurement/monitoring and without the analysis of relevant metrics. Indeed, decision making cannot be realized without knowledge and data on the past, present and even future status of the activity. This is typically the case for agile capacity planning and resource sharing for which usage needs to be computed and even predicted. This is a challenge for which tools coming from AI are very promising. Another relevant example of challenge is measurements for regulation purposes, in relation with our activity on network economics: defining regulation rules means designing measurement procedures to verify that the rules are followed. It is for example required to monitor a neutral behavior of ISPs as expected from the Net neutrality principles. While there exist a few tools towards that goal, they are actually all devoted to very specific hindrances to neutrality (blocking, degradation) for specific types of flows or traffic; a major challenge is to detect any type of non-authorized behavior. Many other actors of the ICT economy, if not all, are barely monitored while an unfair behavior could be seen as harming end users and society. To name some noticeable examples, we can cite CDNs which cache some content at the edge of the network and could unfairly propose a better quality to selected customers, or search engines who can prioritize the web. In all those cases, different and specific techniques have to be designed to analyze and detect unexpected behaviors.

Similarly, managing resources and operations calls for evaluating (measuring) the impact of decisions to determine the most appropriate ones. Modeling and performance evaluation techniques are appropriate and useful solutions at a low cost, without the need to build and run the real system. While we have in the group a long experience on performance evaluation, new challenges keep popping up due to new types of services translated into new problems to be modeled and analyzed through performance evaluation tools, and adaptations or extensions of existing techniques for better decision making. They usually require to develop new appropriate network metrics to assess network service operations effectiveness. Illustrative examples are blockchains. The popularity of blockchain lies in the introduction of the concept of a public distributed ledger shared by all participants of the system without relying on a centralized authority. This distributed ledger records all the transactions between parties efficiently and in a verifiable and permanent way. In order to enjoy higher throughput and self-adaptivity to transactions demand in ICT, it requires the development of a new architecture and thus specific modeling and analysis techniques.

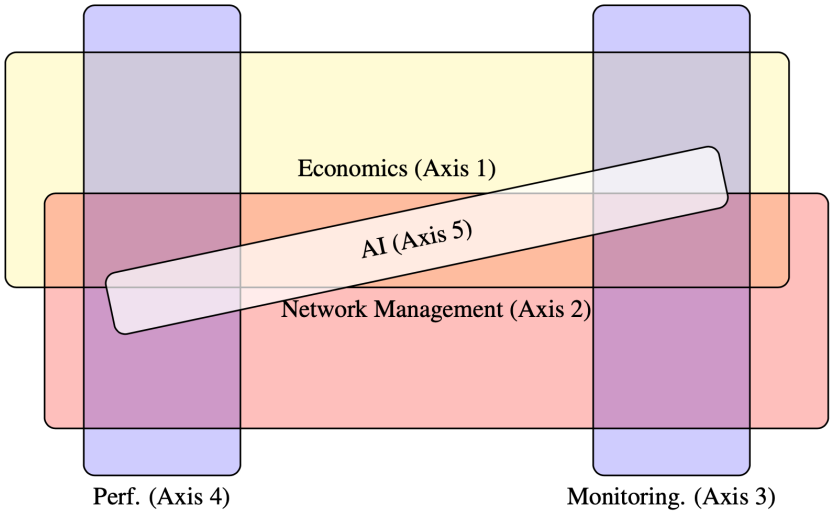



Figure 2: The five research axes: two on network management, two orthogonal on measurements and transverse on AI, with intersections.

## 3.4 Research axes

Our activity is organized in five subtopics (or axes). The first two axes are on network management, and the next two are orthogonal on the associated and required measurements. Axis 5 on AI is transverse. The axes and their intersections are described in Figure 2.

As a brief description:

- **Network Economics.** The digital economy has gained and keeps gaining in scale, scope, and significance. The ecosystem is quickly evolving and one of our main goals is to answer all questions related to the Internet & digital economy that pop up in line with what we started to do, and to be reactive to the news in that domain. We want to address issues concerning Internet resource allocation and pricing models, the economics of services, issues with vertical integration, the economics of structuring platforms, as well as economics and regulation (including network neutrality).

- **Managing next generation networks & massive IoT communication.** One of the fundamental challenges in the traffic management of new and emerging networking activities is to describe, analyze and control heterogeneous resources and complex services, under energy constraints. While AI is a main research direction to address this problem, there exist many other possibilities. The main questions of interest include the automation of infrastructure management (a typical example being network slicing) or the massive access in IoT networks.

- **Measuring, monitoring & regulation.** With the rapid evolution of networks, many needs are appearing for the design of measurement techniques associated with new services, but also for regulators to monitor network's activity. Measurements are of two possible categories: passive, monitoring existing traffic, or active, i.e., based on injecting traffic to investigate the network behavior. The goal of this research direction is to develop practical network operations measurement techniques, from the two different points of view: operators (for a better management) and regulators (for monitoring).

- **Measuring performance metrics based on models.** Measuring performances has to be done not only to observe and monitor directly a service like in previous subsection, but also at different phases such as at conception or to propose enhancements. Indeed, network services management and decision making cannot be applied efficiently without a valid and accurate evaluation of performance metrics through the construction and analysis of models. We are carrying out such evaluations.

- **Artificial Intelligence (AI) in networking.** AI is a transverse research axis, since it is used for both management and measuring. We are not only users of the technology but also interested in the

methodology itself, that is, we also develop new techniques, based on our networking problems but usable outside. This concerns mainly supervised learning, in particular time series forecasting using this type of learning, and reinforcement learning. From the point of view of the tools, our skills and work are essentially related to Random Neural Networks, Reservoir Computing and deep neural architectures in Reinforcement Learning.

# 4 Application domains

Our global research effort concerns networking problems.

The need to support services requiring increasingly high throughput and extremely short latencies in 5G and Beyond 5G (B5G) networks is causing a major transformation of operators' infrastructure. The latter are increasingly being virtualized and expanded to be as close as possible to service consumers, in particular through the development of edge computing. Operators should increasingly collaborate to respond optimally to demands (i.e., cross-domain networks), and eventually converge their networks (i.e., networks' federation). The ultimate solution to this growing complexity is to move towards a fully automated network (i.e., zero-touch network). Our efforts will be dedicated, not on architectural improvements, but on the development of algorithms to manage these infrastructures in an automated way. The efficient and automatic placement of dynamic network services (i.e., network slicing), accommodating simultaneously a wide range of services, is certainly one of the most important concept to move towards zero-touch networks. Similarly, the limited radio resources, the random access to the medium and the spectrum sharing between different applications are critical issues in the IoT context. The focus is not only on 5G and beyond-5G networks, but also on unlicensed networks spectrum such as LoRaWan (for Long Range Wide Area Network; to enable IoT devices to communicate over long distances with minimal battery usage). In LoRaWan networks, the management challenges are even more important given their inherent characteristics, where access is not regulated at all, as it is the case in cellular networks like NB-IoT (for Narrowband Internet of Things).

Still on the management side, with the telecommunications ecosystem quickly evolving, one of our main goals is to answer all questions related to the Internet & digital economy that pop up in line with what we started to do, and to be reactive to the news in that domain to help economic actors and society. Typical and illustrative current questions requiring reactivity are: Is USA repealing neutrality good for some actors in the world, what reactions would be beneficial? Is free roaming in Europe bad for network providers? Is the 2019 Orange-TF1 argument part of the neutrality debate? Should search engines be regulated? Etc. Our goal is mainly to help regulators define proper rules, but we also aim at helping economic actors in decision making (economic choices of CDNs, search engines, etc.) and study their interactions.

On the measurement side, when developing practical network operations measurement techniques, we are interested in two different points of view: operators (for a better management) and regulators (for monitoring). Many of the techniques developed at Ermine are related to the analysis of complex systems in general, not only in telecommunications. For instance, our Monte Carlo methods for analyzing rare events have been used by different industrial partners, some of them in networking but recently also by companies building transportation systems.

# 5 Social and environmental responsibility

## 5.1 Impact of research results

Our research on network economics and particularly neutrality issues aims to view how, and if, regulation can help to improve social welfare, among other goals. Typical examples are how tools SNIDE and DemoWehe described later explaining how potential deviations from rules by respectively search engines and Internet service providers can be detected. Our modeling works on neutrality also allow to investigate the appropriate rules toward a benefice to society. This has led to collaborations with specialists of human sciences in information networks (R. Badouard from Pantheon-Assas and I. Lyubareva from IMT Atlantique) to tackle the socially sensitive issue of bias in information networks, in particular from search engines.

We also work on so-called *green streaming* to analyze the interactions and strategies of various vendors in the market and provide valuable insights that can contribute to the sustainable growth of the Content Delivery Network (CDN) industry. By understanding the implications of energy pricing and its impact on the market

dynamics, this research endeavors to offer potential solutions and recommendations to address the challenges and foster a more sustainable and efficient CDN ecosystem. Similarly, we have started to work on the societal, environmental, and economic impacts of digital infrastructures through a Cifre PhD with Orange Labs.

# 6 Highlights of the year

Chetna Singhal has been recruited as an Inria researcher in 2025.

## 6.1 Awards

The paper entitled "Efficient Key Grouping for Near-optimal Load Balancing in Stream Processing Systems" by E. Anceaume, Y. Busnel, L. Querzoni, N. Rivetti and B. Sericola, which was presented at the 9th ACM International Conference on Distributed Event-Based Systems (DEBS'15), Oslo, Norway, in July 2015, received the "DEBS 10 Years Test of Time Award" at the 19th ACM International Conference on Distributed Event-Based Systems (DEBS'25), Gothenburg, Sweden, in June 2025. This award honors research that has had a lasting and significant impact on the field of distributed event-based systems, even a decade after its original publication. It highlights pioneering work that remains influential and relevant over time.

# 7 Latest software developments, platforms, open data

## 7.1 Latest software developments

### 7.1.1 SNIDE

**Name:** Search Non neutratlIty DEtection

**Keywords:** Search Engine, Statistic analysis

**Scientific Description:** The goal of this tool is, for a search, to collect the ordered lists from the main search engines, to compare them, to perform statistical tests to point out potential outliers, and to propose two meta search engines reducing biases.

**Functional Description:** Different search engines provide different outputs for the same keyword. This may be due to different definitions of relevance, to different ranking aggregation methods, and/or to different knowledge/anticipation of users' preferences, but rankings are also suspected to be biased towards own content, which may be prejudicial to other content providers.

**Contact:** Bruno Tuffin

**Participants:** Patrick Maillé, Bruno Tuffin, Guillermo Andrade Barroso

**Partner:** IMT Atlantique

### 7.1.2 DemoWehe

**Name:** Demontrator of Wehe Net Non-Neutrality Detection Tool on Video Streaming

**Keywords:** Network monitoring, Network neutrality

**Functional Description:** DemoWehe creates a topology made of three virtual machines. One is acting as the Wehe server and one is acting as the client device (or end user). Communications between client and server are done thanks to the third virtual machine representing the network on which service can be differentiated. The same video is played and displayed simultaneously non-differentiated and with the chosen performance degradation. Wehe test is applied and the user can visually evaluate the difference between degradation and possible detection.

**URL:** https://files.inria.fr/wehe_demonstrator/package_wehe.zip

**Contact:** Bruno Tuffin

**Participants:** Patrick Maillé, Bruno Tuffin, Antoine Lesieur

# 8 New results

## 8.1 Network Economics

**Participants:** Burak Kara, Maël Le Treust, Patrick Maillé, Orland-Medy Saizonou, Bruno Tuffin.

Network economics is a key topic to manage and comprehend next generation networks, highlighted by the edited book [36]. From a high level point of view, paper [47] also studies the economic interactions between network stakeholders in next-generation mobile networks. This paper presents a comprehensive analysis of 5G and 6G ecosystems from an economic perspective, including a classification of service classes, applications, and enabling technologies. We map all relevant stakeholders, examine their interactions, and discuss the business models and pricing strategies yielding revenue. It also highlights the regulatory frameworks helping to lead to expected societal outcomes. The study exposes insights on sustainable business strategies and policy development in next-generation communications.

But we also work on specific topics.

**Economics and regulation: network neutrality and network slicing.**

Network slicing, a key feature of next-generation mobile networks, has underexplored economic implications. We model in [28, 48] a Stackelberg game where a mobile operator sells a slice to a service provider offering two service tiers, showing that slicing boosts revenues and improves resource allocation.

**Economics of platforms.**

Digital platforms shape users' choices and opinions through the ranking of the displayed items, the top-ranked ones being more likely to be considered than the next ones. While we expect the ranking to be based on some sort of relevance, there is a suspicion that platforms could alter their ranking to promote some content for financial or economic reasons, among other possibilities. We consider in [45] a model of a ranking platform implementing revenue-maximizing rankings, and analyze the strategy of sellers paying to be ranked higher for a better exposition, thereby increasing sales. We investigate the impact of such strategic behaviors on revenues, overall click rates for all actors, and global relevance perceived by users.

**Search neutrality.**

The digital transformation has revolutionized information consumption, with search engines playing a pivotal role in shaping user access to diverse media. Employing algorithms, these engines influence content visibility and aggregate news sources, significantly molding public opinion. As gatekeepers of information, search engines impact media outlet visibility, affecting online traffic, revenue, and journalistic diversity. In breaking news and societal issues, search engines expedite information dissemination, influencing initial narratives. Focusing on movements against police violence, [1] conducts a comparative analysis across 12 search engines for terms "Black Lives Matter" and "Justice pour Adama". Our innovative methodology identifies biases in information diversity, providing insights into the dynamics shaping visibility of societal issues.

**Platforms regulation.**

The regulation of platforms has been a hot topic, particularly in Europe with the Digital Markets Act (DMA) passed in 2022. The purpose of [22] is to design a mathematical model representing a game between long-term revenue-oriented platforms in competition playing with their ranking strategy of items. The objective of platforms is to apply a trade-off between short-term revenue from each visit by displaying most profitable items and long-term number of visits due to the satisfaction of users from the relevance of the displayed items. We analyze the output of the game and the impact of proposed regulation rules on platforms and users.

Similarly prevailing platforms may be forced by the DMA to share with their competitors some, or all, of the data they collected on users that can help improve service quality. Paper [44] proposes a model to analyze the impacts of such a regulation, by comparing (i) a laisser-faire situation where prevailing platforms are free to sell data to newcomer service providers, (ii) the case when platforms can decide to share data but charging newcomers is prohibited, and (iii) a scenario where data sharing is imposed and enforced by the regulator.

**Economics and energy reduction.**

The increasing focus on the environmental impact of video delivery is reshaping the relationship between content providers (CPs), Content Delivery Network (CDN) vendors, and end-users. In [19], we model the impact of forthcoming energy regulations on the dynamics between CPs, CDN vendors, and end-users.

Somewhat similarly, paper [39] investigates how carbon emissions can be systematically incorporated into telecommunication network capacity planning and pricing decisions for network service providers to respond to their drastic CO2 emission reduction objective. We introduce a model in which user demand depends jointly on price and congestion, while operators face both monetary and environmental costs that scale with capacity and served traffic. In detail, three regulatory scenarios with their strategic interactions are examined through a game theoretic lens. Our results show that environmental constraints can substantially reduce carbon impact; They can even increase social welfare, when environmental costs are high, though often at the expense of operator's revenue. The study offers quantitative insights into how regulators and service providers can balance economic incentives with climate-driven sustainability goals for future computer networks.

**Information coding and decision making.**

Papers [33] and [50] investigate the vector version of the open problem of Witsenhausen (1968). We extend the coding scheme of Le Treust (2017) to the case of a continuous alphabet, adapting the notion of weak typicality. We determine new coding strategies and evaluate their performance. Interestingly, we show that a pair of auxiliary random variables, one discrete and the other continuous, outperforms both the linear strategy and that of the Witsenhausen counterexample (1968). By judiciously choosing the auxiliary coding variables, we obtain a novel compromise, better than previous solutions.

Paper [6] investigate two unsolved zero-error problems: the source coding problem with side information and the channel coding problem. We focus our attention on families of independent problems for which the probability distribution decomposes into a product of probability distributions. A crucial step is the additivity property of the optimal rate, which does not always hold in the zero-error regime, unlike in the vanishing error regime. When the additivity holds, the concatenation of optimal codes is optimal.

## 8.2 Managing next generation networks & massive IoT communication

**Participants:** Soraya Ait Chellouche, Mouloud Atmani, Yassine Hadjadj-Aoul, Wilem Lamdani, Patrick Maillé, Fatima Zahra Mardi, Gerardo Rubino, Chetna Singhal.

**Optimization of Massive-IoT emission strategies.**

Long-Range Frequency-Hopping Spread-Spectrum (LR-FHSS), the latest LoRaWAN physical layer standard, was designed to enhance the uplink capacity of these networks, a prerequisite for direct-to-satellite Internet of Things deployments in areas lacking terrestrial infrastructures. As LR-FHSS still employs an unslotted ALOHA channel-access scheme, its network behavior can be accurately captured using the classical ALOHA model. In [34], we introduce the Multi-Class Multi-Channel ALOHA-based Model (MC2AMB), a novel analytical model that accurately approximates packet delivery success ratios and other metrics, enabling comprehensive evaluation of LR-FHSS networks without requiring computationally expensive simulations. Simulation results demonstrate that MC2AMB accurately estimates network performance across various density scenarios, outperforming state-of-the-art models in this regard. Furthermore, the model enables determining optimal values for key parameters by leveraging its derivatives, providing valuable insights for network optimization.

Beyond the specific constraints of massive-IoT connectivity, optimizing resource allocation remains a critical bottleneck across the entire wireless landscape. As networks evolve to handle a surge in user equipment, enhancing spectral efficiency becomes paramount for higher throughput. Traditional schedulers,

such as Maximum Signal-to-Noise Ratio (MaxSNR), Proportional Fair (PF) perform well in specific contexts, but can be outperformed in others. Moreover, there are many possible schedulers to try in order to find the best ones for diverse contexts. An approach that uses Artificial Intelligence (AI) becomes a conceivable solution. In [32] we introduce a new AI tool that selects and evaluates schedulers that enhance spectral efficiency for different contexts. Our approach is to train the AI model on several traffic loads, to evaluate and select schedulers based on a general scheduling formula, resulting in an explainable model for traffic scheduling. After the training, the appropriate scheduler is used for each traffic load condition. In addition, our tool detects terms of the formula that do not have a positive impact on enhancing spectral efficiency. Simulation results show that the obtained scheduler outperforms state-of-the-art algorithms such as RR, MaxSNR and PF.

**Conflict-Free Scheduling for Industrial IoT Networks.**

The Industrial Internet of Things (IIoT) architecture is designed to minimize latency and transmission errors in industrial communication networks. The IEEE 802.15.4e Time-Slotted Channel Hopping (TSCH) protocol was introduced to provide high reliability and robustness against interference in such environments. However, collisions and external interferences in the native TSCH protocol can still degrade network latency and other key performance metrics. To address these limitations, we work on proposing a Conflict-Free Daisy Chain Scheduling (DCS)-TSCH, an enhanced and deterministic scheduling mechanism for IIoT networks. DCS-TSCH is designed to avoid collisions and reduce interference, thereby improving network performance and consistency.

**UAV-Assisted Mobile Edge Computing for IoT Task Offloading.**

The paper [2] investigates efficient task distribution for computation-intensive IoT devices in urban environments where direct connectivity to edge servers is hindered by infrastructure barriers and network congestion. We focus on multi-UAV-assisted architectures where UAVs act as communication relays collaborating with heterogeneous edge servers to facilitate service delivery. A crucial strategy is the joint optimization of IoT-UAV-ES associations and UAV network topology through preference-based stable matching and adaptive UAV deployment. When this approach is properly optimized, the system effectively maximizes service provider profit while ensuring user satisfaction through stringent latency guarantees and seamless connectivity to remote IoT devices.

**Optimization of EV charging strategies through reinforcement learning.**

To maximize the use of renewable energy, and tackle its variability and uncertainty, flexible entities such as electric vehicles can be used. The contributions [20, 21] present a scalable, decentralized multi-agent system, where each electric vehicle (EV) seeks the best instants to charge to satisfy its mobility needs, while favoring photovoltaic energy and avoiding congesting the electric network. Each EV makes autonomous decisions using information from its environment, using contextual multi-armed bandit algorithms based on Thompson sampling.

## 8.3 Measuring, monitoring & regulation

**Participants:** Yassine Hadjadj-Aoul, Burak Kara, Patrick Maillé, Gerardo Rubino, Bruno Tuffin.

Our activity on monitoring has focused in 2025 on specific contexts.

**Network neutrality monitoring.**

Network neutrality is a sensitive topic worldwide. Laws are passed and regulators are expected to monitor providers activities to check if they conform to the enacted rules. Therefore, tools need to be designed towards that goal but require strong theoretical validations if used for justifying legal actions. Our paper [43] reviews the statistical grounds of the proposed tools, focusing in particular on Wehe, co-designed by the French regulator ARCEP. We provide a statistical analysis of the method used in Wehe, compared with standard ones.

**Network slices monitoring.**

In the context of the SmartNet DEFI collaboration between Nokia Bell Labs and Inria, we work on proposing a novel generalizable Network Tomography framework based on Graph Neural Networks (GNNs) [38]. Addressing the limitations of classical algebraic and statistical inference methods, which are often rigid and struggle with dynamic topologies , our approach leverages Relational Graph Convolutional Networks (RGCN) and Line Graph transformations. This architecture ensures structural invariance, enabling the model to learn from a minimal set of monitors (e.g., just two) and generalize to any other configuration without retraining. This effectively achieves "zero-shot inference", offering a robust and scalable solution for real-time network observability.

**Passive network monitoring and troubleshooting from within the browser.**

Despite advances in network technologies, slow web browsing remains a persistent issue, and its troubleshooting continues to be challenging. To address this challenge, in [15], we presents a lightweight passive measurement solution that relies on web performance data readily available within the browser, such as the connect time, the response time, and the page load time, to infer network performance, detect anomalies, and troubleshoot their origins. Through controlled network experiments with manually injected anomalies, including multiple concurrent performance issues, and leveraging a dataset of more than 43, 000 webpages and tens of thousands of network scenarios, we develop a predictive model using machine learning that is capable of estimating network performance metrics with acceptable accuracy. By solely relying on users' daily web activity, our solution can continuously monitor network performance, identify anomalies, and provide actionable insights, without overloading the network with measurement probes, thus making network troubleshooting accessible and non-intrusive for everyday users.

**CDNs.**

The content providers now leverage multiple Content Delivery Networks (CDNs) to distribute the video streams. Content steering is the main technology for the implementation of smooth and dynamic multi-CDN orchestration. [17] addresses the question: how to get informed about the recovery of a faulty CDN if no users are downloading from it?

Short-form videos have emerged as a dominant force in online media, they now account for a substantial share of global media consumption. [18] analyzes a dataset of short-form videos from a popular news application, which includes metrics related to videos consumed within the app in a format akin to YouTube Shorts or Instagram Reels. Building on these insights, the paper poses open questions and advocates for community-driven efforts to establish open protocols for short-form video content.

**Performance of a Lightweight Consensus Cryptographic Protocol in WBANs.** Wireless Body Area Networks (WBANs) play a critical role in healthcare by enabling real-time monitoring through wearable devices. Blockchain technology improves data integrity and security in WBANs, but introduces significant transmission and energy challenges due to the constrained nature of these networks. [14] evaluates a lightweight consensus protocol that uses Practical Byzantine Fault Tolerance (PBFT) principles, tailored to WBAN requirements, proposed by part of the authors in previous work. Our study considers the main dynamics of the system, such as activation and deactivation rates, as well as packet generation rates and transmission durations. Through packet-level system simulations, the reliability and efficiency of the protocol are analyzed. This work provides actionable insights into optimizing blockchain-based WBAN systems, highlighting the tradeoffs between node activation rates and network stability.

## 8.4 Measuring performance metrics based on models

**Participants:** Gerardo Rubino, Bruno Sericola, Bruno Tuffin.

Our work on performance analysis in 2025 can be decomposed in simulation, with application to resilience, transient and equilibrium analysis, with application to protocols, and distributed systems. It concerns both teoretical and practical problems.

**Monte Carlo simulation.**

We have continued our work on rare event simulation.

Consider an estimand that is a known smooth function of an unknown vector of parameters, such as means, probabilities, quantiles, etc. Some but not necessarily all of the parameters relate to rare events, which typically make them difficult to estimate with naive Monte Carlo, so variance-reduction techniques must to be applied to obtain efficient estimators of those parameters. We develop in [46] conditions ensuring that the overall estimand can be efficiently estimated, providing both sufficient and necessary and sufficient conditions on the parameter estimations to lead to an efficient overall estimation. The paper illustrates the applicability of the theory through many examples and numerical results.

**Randomized Quasi-Monte Carlo.**

Consider again estimating a known smooth function (such as a ratio) of unknown means. [23] accomplishes this by first estimating each mean via randomized quasi-Monte Carlo and then evaluating the function at the estimated means. We prove that the resulting plug-in estimator obeys a central limit theorem by first establishing a joint central limit theorem for a triangular array of estimators of the vector of means and then employing the delta method.

**Network reliability.**

Network reliability computation is an NP-hard problem which has attracted much attention in literature. Given the difficulty to compute the exact value of this metric, an alternative which has been much explored in the literature is the use of Monte Carlo estimation methods. In [3], we discuss Permutation Monte Carlo, a highly efficient network reliability estimation method but prone to numerical limitations for large networks. We present a simple way to rewrite the algorithm's calculations to make it numerically more stable. We also present a variant implementation for homogeneous models (when all the links share the same failure probability). For this type of network the procedure can be redesigned to be much more efficient. We present some experimental test results proving that both proposed implementation variants perform extremely well.

**Markov chains.**

Sigmund duality makes a connection between arbitrary irreducible Markov chains and specific absorbing ones. In [11], we present a different way of connecting both classes of chains, that proves useful in the analysis of their steady-state regime (for absorbing chains, instead of the useless steady-state probabilities we work with absorption probabilities and with mean absorption times). The connection we discuss also considers arbitrary irreducible models, which are associated with specific absorbing chains, but with a totally different structure than when using duality.

[12] deals with the performance analysis of a system modeled by a Markovian queue in its transient phase. Instead of considering the classical transient distribution of the model's state, we focus on the maximal number of customers in the system, in the interval $[0,t]$. Since this is a random variable, we evaluate its distribution. The numerical scheme that we propose is based on the Uniformization procedure, and we illustrate it on the $M/M/1$ and $M/M/1/H$ models. We also show how to analyze another metric, namely the fraction of lost customers in a finite storage model, following a similar approach.

The chapter [35] discusses two different but related problems: the analysis of the regions of the models' parameters where generalized steady-state distributions exist, for certain real *somewhat stochastic* matrices $P$, and the known relationship between the generalized steady-state distribution $\pi$ of matrix $P$ and Gambler's ruin probabilities defined in the algebraic dual $P^*$ of $P$, using our extension to Siegmund duality to arbitrary matrices. The article is illustrated with many examples of Markovian queueing systems.

**Measuring the performance of distributed systems.**

Distributed systems protocols and network protocols sometimes make use of random walks (i.e., token circulation) on such systems, to explore them in order to collect information from them and to make systems reliable. Important performance measures of these protocols such as the search time and the time to visit all the sites obviously depend on some quality measures on random walks such as the hitting and the cover times. The cover time of a discrete-time homogeneous Markov chain or of a random walk is the time needed to visit all the states of the process. We analyze in [4] the moments and the distribution of hitting times on the lollipop graph which is the graph exhibiting the maximum expected hitting time among all the graphs having the same number of nodes. We obtain recurrence relations for the moments of all orders and we use

these relations to analyze the asymptotic behavior of the hitting time distribution when the number of nodes tends to infinity. We consider in [5] the moments and the distribution of the hitting and cover times of a random walk in the complete graph. We study both the time needed to reach any subset of states and the time needed to visit all the states of a subset at least once. As we did for the lollipop graph, we obtain recurrence relations for the moments of all orders and we use these relations to analyze the asymptotic behavior of the hitting and cover times distributions when the number of states tends to infinity. The same type of results have been derived in [49] for the path graph and in [41] for both the star graph and the sun graph.

Continuing our collaboration with the Pirat Inria Team, We consider in [40] a large scale and permissionless system, that is a system in which users can join and leave at any time without any preliminary indication to their application. We also consider that a percentage of these users are malicious, that is exhibit an arbitrary behavior. These users can collide together. This is modeled by an oblivious adversary. In such a system, we propose a probabilistic consensus algorithm that allows all the correct users to decide on the same set of values. Specifically, with any probability larger than $1-\varepsilon$, if any two correct users decide a set of values, then those sets are exactly the same. This holds even if the adversary tries to prevent convergence to the same set of values. Handling the adversarial nature of the system is achieved through proof-of-eligibility, ephemeral participation and the introduction of a broadcast factor $\lambda$. Altogether, they guarantee with probability larger than $1-2\varepsilon$ that any transaction initially broadcast by any correct user will belong to the decision value, and that any two decision values contain exactly the same set of transactions, whatever the adversarial nature of the execution. Finally, any consensus execution terminates in six asynchronous rounds. A straightforward application of our consensus algorithm is the design of permissionless distributed ledgers.

Our work on the comparison of population protocols has led us to analyze the stochastic ordering of random variables. The stochastic ordering is usefull to compare random variables in terms of their probability distribution: if $X$ and $Y$ are two real random variables, we say $X$ is less than $Y$ in the usual stochastic ordering whenever $P(X > x) \leq P(Y > x)$ for all $x \in \mathbb{R}$. We then write $X \leq_{\mathrm{st}} Y$. For instance if $X$ and $Y$ are two durations then $X \leq_{\mathrm{st}} Y$ means that for all values of $x$, the duration $X$ has less chances to exceed $x$ than duration $Y$. In [42], we consider the case of sums of independent and exponentially distributed random variables: if $X_i$, resp. $Y_i$ $(i = 1, \ldots, n)$, are independent random variables that are exponentially distributed with rates $\lambda_i$, resp. $\mu_i$, we examine under which conditions on the $\lambda_i$'s and $\mu_i$'s one can ensure $\sum_{i=1}^{n} X_i \leq_{\mathrm{st}} \sum_{i=1}^{n} Y_i$.

Adopting a geomeric point of view in the space of the parameters $\lambda_i$ and $\mu_i$, we come up with close to optimal conditions, improving previous results on this question, as well as shedding a geometric light on known results.

## 8.5 Artificial Intelligence (AI) in networking

Here, we are covering many different topics in AI methods applied to networking problems, together with some more methodological work.

**Participants:** Soraya Ait Chellouche, Yassine Hadjadj-Aoul, Gerardo Rubino, Chetna Singhal, Lucas Taucoory, César Viho.

**Green AI and Quantization for 6G.**

With the integration of AI as a native component of 6G infrastructure, the energy consumption of ML models becomes a critical concern. Paper [31] investigates the impact of post-training quantization on LSTM, CNN, and Transformer models for the predictive handover use case. We benchmark quantized and full-precision models on both CPU and GPU platforms to evaluate accuracy, latency, and energy consumption. Our results show that while quantization on CPUs delivers notable energy improvements, particularly for CNN architectures and small batch sizes, the gains on GPUs are inconsistent due to limited INT8 support for sequence-based models. The study provides practical guidance for deploying quantized models in telecom environments, demonstrating that energy efficiency can be improved without compromising predictive accuracy.

**Orchestration of Dynamic AI for Network Modeling.**

Paper [30] investigates the problem of efficiently orchestrating Graph Neural Networks (GNNs) for adaptive network modeling in mobile-edge-cloud continuum systems. We focus our attention on heterogeneous network modeling applications with diverse quality-of-service (QoS) and latency requirements that must be met through dynamic configuration selection and compute node assignment. A crucial step in our approach is the representation of the system using a tripartite graph model that captures the relationships between applications, GNN model configurations, and heterogeneous computing resources (CPUs, GPUs, and TPUs). When the energy-efficient configuration selections are properly optimized through quantum approximate optimization (QAO), the dynamic orchestration of training, updating, and inference tasks yields near-optimal energy efficiency while meeting the stringent application requirements. Our framework, QAG, demonstrates that this adaptive orchestration strategy achieves at least 50% energy savings and 60% lower churn-rate compared to existing fixed-configuration approaches.

**Network Traffic Classification for Multi-Activity Situations Detection.**
Classifying network traffic is one of the most crucial aspects of monitoring. The major contribution of this work [37] resides in the development of the SMAR (Single and Multi Activity Recognition) framework. The main objective of the framework's conception was to address the complex and real-life situation of a user engaging in multiple digital activities simultaneously. In order to achieve this objective, we first provided our proper conceptual and operational definitions of this concept (i.e., multi-activity situations). Then, a methodology was proposed for the generation of multi-activity network traces from single-activity traces, which was then implemented. This methodological approach facilitated the establishment of a unique and essential dataset for the training and validation of the proposed solution. The evaluation of the SMAR framework, based on deep learning models and more specifically a multi-task learning architecture, has shown very encouraging performance. The outcomes of this study not only confirmed the effectiveness of the proposed methodology in successfully differentiating between single-activity and multi-activity scenarios, but also in accurately identifying the types of activities and applications involved.

**Federated Representation Learning for Application Type Detection in Future Mobile Networks**.
Mobile application classification is essential for advanced network management and application-based QoS policy enforcement in future, AI-enhanced, beyond 5G and 6G mobile networks. We propose to use AI methods to categorize applications as functional types (e.g., Video, Audio, Browsing) despite encryption and limited labeled data. This year, we tackle these challenges through unsupervised representation learning, which maximizes the use of abundant unlabeled data in mobile networks. Due to the distributed nature of beyond 5G and 6G networks, we use this method in federated learning scenarios and compare it to the centralized ones. Our findings highlight that unsupervised learning improves model performance, especially with scarce labeled data. Additionally, federated learning provides effective results as compared to centralized methods [16].

**Advanced AI for Sustainable and Proactive 6G Orchestration.**
Realizing the vision of 6G requires orchestrators that are not only intelligent but also energy-conscious and privacy-preserving across distributed domains. We currently address these challenges through two complementary frameworks that leverage advanced Deep Reinforcement Learning (DRL).

First, to enable proactive resource management without compromising domain privacy, we introduce the HERO framework [24, 51]. This framework couples DRL with Latent Ordinary Differential Equations (Latent ODEs) to encode historical states into privacy-preserving latent spaces. By exchanging these latent states and aggregating them via a gated attention mechanism, distributed orchestrators achieve a holistic vision of the network's future, allowing them to anticipate inter-domain traffic shifts effectively.

Second, addressing the specific challenge of sustainability during scaling operations, Paper [13] proposes a distributed, energy-efficient placement framework. This approach utilizes a Graph Neural Network (GNN) to encode the complex substrate topology and resource states, feeding this representation into a DRL agent, optimizing a refined energy consumption model that accounts for both computational and network-level power usage.

**ML-based Network Slicing.**
Beyond standard AI approaches, metaheuristics offer powerful tools for solving the NP-hard Virtual Network Embedding (VNE) problem in 6G slicing. We propose a robust optimization framework based on

the Greedy Randomized Adaptive Search Procedure (GRASP). In [25], we tackle the challenge of service reliability by introducing a two-phase optimization process: an initial resource-efficient placement followed by a reliability enhancement phase. This method achieves significant improvements in placement reliability compared to traditional heuristics. Complementing this, paper [26] addresses the issue of local optima in placement algorithms. We propose an Enhanced Exploration GRASP that expands the search space through a broader candidate selection and a multi-level neighborhood search, yielding superior success rates and revenue-to-cost ratios for complex service requests.

**Enhancing Autonomous Driving Navigation Using AI.**
The multimedia streaming can be challenging in resource constrained dynamic environment [8]. The paper [29] investigates the problem of enabling safe autonomous navigation and high-level autonomy tasks such as exploration and surveillance for resource-constrained nano-sized platforms in partially-known environments. To support the robust connectivity required for such tasks, the paper [7] introduces a low-complexity modified pilot-based channel estimation (MPCE) method for IEEE 802.22 systems that achieves up to 78% reduction in runtime. In [29], we focus our attention on a pocket-size 30-gram Crazyflie 2.1 drone equipped with an ultra-low-power greyscale camera and limited onboard computational resources. A crucial strategy is the splitting of the navigation task between edge and onboard computing, wherein a deep learning-based object detector executes on external hardware while the reactive planning algorithm runs on the drone itself. When this split-computing approach is properly optimized through integrated sensing, computing, and communication (ISCC) paradigm, the autonomous navigation system achieves a command rate of approximately 8 frames-per-second and object detection performance of 60.8 COCO mean-average-precision. Field experiments validate the feasibility of the framework with successful autonomous flight at speeds up to 1 m/s, demonstrating safe obstacle avoidance and waypoint navigation in unknown environments while maintaining real-time compatibility between communication delays and perception requirements.

**Dynamic AI Orchestration for Energy-Efficient Inference in Distributed Network System.**
The paper [9] addresses dynamic deployment of gated neural networks with context-aware sensor fusion across heterogeneous infrastructure. It develops quantile-constrained inference optimization for joint orchestration of data sources, DNN architectures, and resource allocation. The paper [10] focuses on distributed execution of DNNs equipped with early exits in mobile-edge-cloud systems. It introduces feasible inference graphs to optimally determine layer splitting and deployment locations. Together, these approaches achieve adaptive, energy-efficient inference that satisfies application latency and quality requirements. Both papers demonstrate dramatic energy reductions through intelligent model splitting and context-aware configuration selection, enabling efficient AI-driven applications across resource-constrained network infrastructure.

**Forecasting Seasonal Extreme Temperatures.** In recent years, great progress has been made in the field of forecasting meteorological variables, but the progress is much slower in predicting climatological metrics. In [27], we consider the maximum daily temperatures in the short, medium, and long term. A common approach here is to frame the study as a temporal classification problem with the classes “maximum temperature above normal, normal or below normal". From a practical point of view, we created a large historical dataset (from 1981 to 2018) collecting information from weather stations located in South America, plus exogenous data from the Pacific, Atlantic, and Indian Ocean basins. We present the different aspects of this work, finally based on the use of the AutoGluonTS platform. We obtain results similar than those of the litterature, but using a single and standard server instead of huge hardware platforms.

# 9 Bilateral contracts and grants with industry

## 9.1 Bilateral contracts with industry

### 9.1.1 DEFI SmartNet

**Participants:** Soraya Aït-Chellouche, Yassine Hadjadh-Aoul.

**Title:** SmartNet “AI methods for smart network management”

**Partner Institution(s):**

- Nokia Bell Labs
- Inria

**Date/Duration:** Nov. 2023-Dec. 2027 (4 years)

**Summary:** The objective of the SMARTNET project is dedicated to exploring the transformative potential of AI methods in enabling smart network management. The project strategically focuses on two key areas: slice provisioning and causal analysis of network malfunctions. The project involves several teams in Inria (Aptikal, Coati, Ermine, Neo, Spades, and Stack) and the work of several PhD students and postdocs. Yassine Hadjadj-Aoul is the coordinator of the DEFI SmartNet.

#### 9.1.2 ANR Genie

**Participants:** Soraya Ait Chellouche, Yassine Hadjadj-Aoul, Gerardo Rubino.

**Title:** Generative Network Intelligence and Optimization Ecosystem.

**Partner Institution(s):**

- Université de Rennes
- Côte d’Azur University
- Jean Monnet University
- La Rochelle University
- IMT Atlantique

**Date/Duration:** Oct. 2024-Oct. 2028 (4 years)

**Summary:** GENIE aims to revolutionize network infrastructure management by leveraging Large Language Models (LLMs) and domain-specific expertise. It focuses on creating automated, adaptable, and interpretable network management solutions by translating high-level intentions into optimized configurations. The project will design an LLM pipeline for efficient decision-making using collaborative and evolutionary strategies. GENIE aims to advance network infrastructure management and contribute to AI-driven network automation.

#### 9.1.3 ANR EDEN4SG

**Participants:** Patrick Maillé.

**Title:** Efficient and Dynamic ENergy Management for Large-Scale Smart Grids

**Partner Institution(s):**

- Orange Labs
- Université Toulouse 3 - Paul Sabatier
- CNRS
- IMT Atlantique/IRISA
- EDF
- SRD

**Date/Duration:** January 2023-January 2027 (4 years)

**Summary:** The wide-scale deployment of electrical vehicles (EVs) represents a challenge as well as an opportunity to render more efficient and affordable the transformation of the current power system into a smarter grid. The goal of the project is to develop more efficient, decentralised, and dynamic energy management methods able to ensure coordination of large-scale fleets of EVs with conflicting objectives/constraints. In addition, the energy management of power systems closer-and-closer to real-time will require the intensive use of pervasive information and communication technologies (ICT). These technologies may suffer from an imperfect quality of service (QoS) (e.g. delays) which may greatly decrease the performance of smart grids.

## 9.2 Bilateral Grants with Industry

### 9.2.1 CRE on SCHC with Orange

**Participants:** Patrick Maillé.

This 12-month project aims to expand and optimize the use of SCHC (Static Context Header Compression) technology beyond its initial application in LPWAN (Low Power Wide Area Network) networks. The collaboration revolves around three major objectives: developing solutions for efficient SCHC session management in multi-hop IP networks, designing mechanisms for automatic SCHC rule generation through machine learning, and evaluating SCHC's potential impact on various network technologies (4G/5G, NTN, optical fiber). The goal is to improve energy efficiency and resource utilization in telecommunications networks by optimizing packet header compression while ensuring viable implementation on constrained embedded systems.

### 9.2.2 Sustainable AI Integration in 6G Networks: Energy Efficiency and Environmental Impact Optimization

**Participants:** Yassine Hadjadh-Aoul.

This is a Cifre contract 2025-2028 including a PhD thesis supervision (PhD of Lucas Taucoory), with Nokia standards (Nozay) and Inria, tackling the challenges of sustainability by design in the context of 6G, with a focus on Sustainable AI and associated fields such as data frugality and AI/ML traffic load management. While the integration of AI into 6G networks offers benefits like optimized power allocation and reduced idle resource usage, the models themselves demand significant computational power which affects energy consumption. The thesis objectives include establishing sustainability metrics, developing energy models, and proposing novel energy optimization approaches tailored specifically to 6G. The work plan concludes with integrating the proposed solutions into a practical testbed environment to validate methodologies for reducing carbon emissions and improving energy efficiency.

### 9.2.3 Cifre on safe resource management in 6G with distributed decision making

**Participants:** Soraya Aït Chellouche, Yassine Hadjadh-Aoul.

This is a Cifre contract 2023-2026 including a PhD thesis supervision (PhD of Parsa Rajabzadeh), done with Nokia Bell Labs (Nozay) and Inria, on IA/ML driven safe resource management in 6G with distributed decision making. The objective of the thesis is to propose a trusted and scalable scheduling strategies for managing network resources in a multi-level distributed context with a distributed decision-making using artificial intelligence (e.g.,multi-agent deep reinforcement learning).

#### 9.2.4 Cifre on societal, environmental, and economic impacts of digital infrastructures

**Participants:** Patrick Maillé.

Cifre contract 2024-2027 with Orange (PhD thesis of Nogbou Henriette Grâce Bénédicte Kongo) mixing economy, sociology and applied mathematics on the impact of digital infrastructures.

#### 9.2.5 Cifre on green video streaming: modeling, evaluation and regulation

**Participants:** Bruno Tuffin.

This is a Cifre contract 2023-2025 including a PhD thesis supervision (PhD of Burak Kara), done with Synamedia, on the modeling of end-to-end streaming for a greener distribution. The goal is to determine which strategies could allow to reduce the energy impact of streaming. Thoses strategy can be implemented via a regulator. We can think of economic regulation, through taxes and/or incentives, or of technical regulation by imposing constraints.

#### 9.2.6 Contract with InterDigital "UX-Centric Adaptation of Multi-User Real-Time XR Applications Over Wireless Network"

**Participants:** Sofiene Jelassi, Bruno Tuffin.

This project funds the PhD of Etienne Faivre d'Arcier. This doctoral research work aims to investigate how a real-time multi-user XR (for eXtended reality) application running over a wireless network can be enhanced through adaptation actions that enable providing an optimal User eXperience (UX). Extensive user studies are conducted to evaluate the impact of both the adaptation mechanisms and the multi-user situation on User eXperience.

# 10 Partnerships and cooperations

## 10.1 International initiatives

### 10.1.1 Associate Teams in the framework of an Inria International Lab or in the framework of an Inria International Program

**IoT4Pest**

**Title:** Smart Sensors Networks for monitoring Agricultural Environment: Applied to Pest monitoring in Farm of Sub-Saharan Africa

**Duration:** 2024 -> 2026

**Coordinator:** Arnaud Ahouandjinou (arnaud.ahouandjinou@imsp-uac.org)

**Partners:**

- Université d'Abomey-Calavi, Bénin (Bénin)

**Inria contact:** Cesar Viho

**Summary:** The main scientific goal of this research work in collaboration is to propose a smart system for digitized agriculture. This project focuses on a new agronomic challenge in the context of agroecology through the development of a new digital method of pest control based on an intelligent crop monitoring network system. The proposed approach is based on smart sensors by combining a set of usual agricultural parameter measurement sensors (temperature, humidity) and electronic nose type sensors for the measurement of volatile substances in the environment of the caterpillar using a brand new electronic system to design in order to detect early caterpillars. This project aims at developing a sensor-based system for the early detection of pests in agricultural fields. Specifically, it is initially a question of designing a global architecture of smart monitoring systems dedicated to best managing human activities and crop growth.

**CONNECT**

**Title:** Communication Network Norms Encouraging Community Transformation

**Duration:** 2025 ->

**Coordinator:** Jorn Altmann (jorn.altmannu@acm.org)

**Partners:**

- Seoul NAtional University, South Korea

**Inria contact:** Bruno Tuffin

**Summary:** Telecommunication networks and ICT (for Information & Communications Technology) are omnipresent in our modern society, and have profoundly changed the economy, from the industrial era to the communication era. Designing and analyzing business models for ICT, taking into account their acceptance by end users, is a key issue in that respect, as the way markets are run affects the outcome for all players (who act selfishly in most cases) individually, but also the benefits for society as a whole. Therefore, the role of regulators in determining rules that actors need to follow in order to avoid harmful behaviors, ideally maximizing social welfare, is crucial. Thanks to the modeling of economic interactions, both teams address those questions: the design of economic rules for new services, the analysis of the impact of players' decisions and interactions, and the potential design of rules or incentives from regulatory bodies leading to the most adequate (social) outcomes. Among the frameworks commonly used is that of game theory, and in particular the field of mechanism design

## 10.2 International research visitors

### 10.2.1 Visits of international scientists

**Other international visits to the team**

**Yijie Peng**

**Status** Professor

**Institution of origin:** Peking University

**Country:** China

**Dates:** January 14-15 2025

**Context of the visit:** Collaboration on Monte Carlo methods

**Mobility program/type of mobility:** research stay

**Pierre L'Ecuyer**

**Status** Professor

**Institution of origin:** Université de Montréal

**Country:** Canada

**Dates:** March 31-April 13 2025

**Context of the visit:** Collaboration on quasi-Monte Carlo Methodologies

**Mobility program/type of mobility:** research stay

**Hector Cancela**

**Status** Professor

**Institution of origin:** Universidad de la República

**Country:** Uruguay

**Dates:** April 14-April 20 2025

**Context of the visit:** Collaboration on simulation and reliability

**Mobility program/type of mobility:** research stay

**Tobias Oechtering and Mengyuan Zhao**

**Status** Professor and PhD

**Institution of origin:** KTH

**Country:** Sweden

**Dates:** 19th-22th May 2025

**Context of the visit:** Collaboration VR project

**Mobility program/type of mobility:** research stay

**Marvin Nakayama**

**Status** Professor

**Institution of origin:** New Jersey Institute of Technology

**Country:** USA

**Dates:** May 19-May 24 2025

**Context of the visit:** Collaboration on Monte Carlo and quasi-Monte Carlo methods

**Mobility program/type of mobility:** research stay

**Nashid Shahriar**

**Status** Associate Professor

**Institution of origin:** University of Regina

**Country:** Canada

**Dates:** 3rd–8th July 2025

**Context of the visit:** Collaboration on energy-efficient slice embedding

**Mobility program/type of mobility:** research stay

## 10.3 National initiatives

### 10.3.1 PEPR 5G and future networks

**Participants:** Yassine Hadjadj-Aoul, Maël Le Treust, Patrick Maillé, Bruno Tuffin.

We participate to the project NF-MUST of the PEPR 5G and Future Networks. It focuses mainly on transforming client requests into end-to-end service orderings and on mapping them to resources and network level services (to be) provisioned by the multiple underlying networks. There is a clear evolution of 5 and 6G networks towards the provisioning of services involving multiple players and multiple technologies. Project NF-MUST addresses the related roles and interactions between customers and multiple domains in connection to the other "PEPR 5G and Future Networks" projects, to ensure automated production and operation of multi-domain services across multiple providers. Besides ordering services, NF-MUST will drive the management of the life cycle of the infrastructures, provisioned services, and partake in their dynamic and automated adaptation and operation.

We also participate to the project NF-FOUNDS of the PEPR 5G and Future Networks. Distributed algorithms allowing one to reach or approximate the fundamental limitations of wireless networking are central to 5 and 6G networking. In this project, we investigate the fundamental limits of decentralized decision problems, that rely on coding algorithms for the coordination of autonomous devices.

### 10.3.2 Inria pilot-project REGALIA

**Participants:** Patrick Maillé, Bruno Tuffin.

The Regalia pilot project, led by Inria, aims to build a software environment for testing and regulation support to address the risks of bias and disloyalty generated by the algorithms of digital platforms. We participate to this project through the development of the demonstrator DemoWehe on the supervision and detection of differentiated behaviors for Internet service providers.

## 10.4 Regional initiatives

### 10.4.1 Informal local partners

**Participants:** Bruno Sericola.

We collaborate with Emmanuelle Anceaume (Inria team Pirat) and François Castella (Inria team Mingus) on the analysis of population protocols and of random walks on graphs.

# 11 Dissemination

**Participants:** Soraya Ait Chellouche, Yassine Hadjadj-Aoul, Sofiene Jelassi, Mael Le Treust, Patrick Maillé, Gerardo Rubino, Bruno Sericola, Chetna Singhal, Bruno Tuffin, Cesar Viho.

## 11.1 Promoting scientific activities

### 11.1.1 Scientific events: organisation

**General chair, scientific chair**

- Bruno Tuffin has been the Chair of the Steering Committee of the International Conference on Monte Carlo Methods and Applications (MCM) series since August 2021.

- Bruno Tuffin is member of steering committee os the International Conference on Network Games, Control and Optimization (NETGCOOP).

- Yassine Hadjadj-Aoul is chairing the steering committee of the International Conference on Information and Communication Technologies for Disaster Management (ICT-DM).

- Yassine Hadjadj-Aoul served as the general co-chair of the "AI & Infrastructure" Days, within the **GDR RSD, CNRS** (December 2025).

- Yassine Hadjadj-Aoul served as the general co-chair of the 12th International Symposium on Networks, Computers and Communications (ISNCC) (Co-sponsored by IEEE), Paris, France (October 2025).

- Gerardo Rubino and Bruno Tuffin are members of the Steering Committee of the International Workshop on Rare Event Simulation (RESIM).

**Member of the organizing committees**

- Maël Le Treust co-organizes of the conference 30 Years of Game Theory at Institut Henri Poincaré, 6th-10th October 2025.

- Mouloud Atmani was a member of the organizing committee for the IS-6G-Tech international school, which took place in Rennes, 12th-14th, November 2025.

**Member of the conference program committees**

- Bruno Tuffin served as TPC member of the 36th International Teletraffic Congress (ITC), the 15th International Conference on Simulation and Modeling Methodologies, Technologies and Applications (SIMULTECH), Monte Carlo Methods (MCM) and IEEE Globecom CSM.

- Maël Le Treust served as TPC member of the IEEE International Symposium on Information Theory (ISIT) and the IEEE Information Theory Workshop (ITW).

- Patrick Maillé served as a TPC member for the IEEE International Conference on Communications (ICC), for the 12th International Conference of Networks, Games, Control and Optimization (NETGCOOP), and for IEEE Globecom.

- Bruno Sericola served as TPC member of the 23rd International Symposium on Network Computing and Applications (NCA 2025).

- Chetna Singhal served as a TPC member for the IEEE International Conference on Computer Communications (INFOCOM), IEEE Global Communications Conference (Globecom), IEEE International Conference on Communications (ICC), IEEE Consumer Communications and Networking Conference (CCNC), and IEEE Vehicular Technology Conference (VTC)-Spring and Fall 2025.

- Gerardo Rubino served as TPC member of the conference MASCOTS'25 (the 33rd International Symposium on the Modeling, Analysis, and Simulation of Computer and Telecommunication Systems, Paris, Oct. 21-23, 2025.

- Soraya Ait Chellouche served as TPC member for IEEE 30th IEEE Symposium on Computers and Communications (ISCC 2025) and IEEE Vehicular Technology Conference (VTC-Spring 2025)

### 11.1.2 Journal

**Member of editorial boards**

- Bruno Tuffin is Area Editor for *INFORMS Journal on Computing* (since Jan. 2016) and Associate Editor for *ACM Transactions on Modeling and Computer Simulation* (since 2009) and *Queueing Systems* (since 2022).
- Gerardo Rubino is Associate Editor for *Journal of Dynamics & Games* and for *Performance Evaluation*.
- Patrick Maillé is an Associate Editor for *Electronic Commerce Research and Applications*.
- Bruno Sericola is Editor in Chief of the books series "Stochastic Models in Computer Science and Telecommunications Networks", ISTE/WILEY.
- Maël Le Treust serves as associate editor for IEEE Transactions on Information Theory, Area Privacy and Security (1st term: Oct. 2021 - Sept. 2024, 2nd term: Oct. 2024 - 2027).

### 11.1.3 Invited talks

- Yassine Hadjadj-Aoul delivered the following invited tutorials, seminars, and conference talks:
  - **Invited Tutorial** — International Conference on Machine Learning for Networking (MLN 2025), Paris, France, December 2025. *Title*: "Graph Neural Networks for Scalable Network Optimization".
  - **Seminar** — Training School on Networks and AI, Paris, France, October 2025. *Title*: "Generalizable Network Optimization: GNN Strategies for Network Slicing and Tomography".
  - **Seminar** — Celebrating 100 Years of Nokia Bell Labs Innovation, Massy, France, June 2025. *Title*: "AI and Network Automation".
  - **National Conference** — National Conference on Intelligent Data Engineering and Advanced Systems (IDEAS 2025), Oran, Algeria, June 2025. *Title*: "Graph Intelligence and Data Engineering for the Future of AI-Driven Networks".
  - **Seminar** — Algotel–CORES 2025, Saint-Valery-sur-Somme, France, June 2025. *Title*: "Advancing Network Slicing Optimization: From Classical Deep Reinforcement Learning to Graph Neural Networks".
  - **National Conference** — National Conference on Connected Systems and Data Intelligence (COSDI 2025), Oran, Algeria, May 2025. *Title*: "Advancing Network Slicing Optimization: From Classical Deep Reinforcement Learning to Graph Neural Networks".

### 11.1.4 Leadership within the scientific community

- Yassine Hadjadj-Aoul is co-head of the **"AI for Infrastructure"** initiative within the **GDR RSD, CNRS** (since January 2025).
- Gerardo Rubino is a member of the Working Group 7.3 "Computer System Modeling" of IFIP.
- Gerardo Rubino is a member of the Multimedia Communications Technical Committee (MMTC) of ComSoc, IEEE.

## 11.2 Teaching - Supervision - Juries - Educational and pedagogical outreach

### 11.2.1 Teaching

- Master: Bruno Tuffin, MEPS (simulation and performance evaluation), 22 hours, M1 University of Rennes, France
- Master: Maël Le Treust, Information Theory, 12 hours, M1 ENS Rennes and University of Rennes, France

- Master: Patrick Maillé (Game Theory and Agent-Based Modeling), 20 hours, IMT Atlantique.
- Bachelor L3: Patrick Maillé (Network performance modeling basics), 20 hours, IMT Atlantique.
- Bachelor L3: Patrick Maillé (Models for semiconductor-based components), 15 hours, IMT Atlantique.
- Master: Patrick Maillé (Economics of Digital Platforms), 15 hours, IMT Atlantique.
- Master, 1st year: Patrick Maillé (Probability and Statistics), 50 hours, IMT Atlantique.
- Master: Patrick Maillé (Convex optimization), 12 hours, Université de Rennes.
- Master: Bruno Sericola, MEPS (performance evaluation), 35 hours, M1, University of Rennes, France.
- Bachelor L3: Bruno Sericola, Probability and Statistics, 20 hours, IUT GEII University of Rennes, France.
- Master M2: Chetna Singhal, SNI, 3 hours, ISTIC University of Rennes, France.
- Master M1-Cloud and Networks: César Viho, Networks : from Services to protocols, 36 hours, ISTIC Université de Rennes, France.
- Bachelor L3: César Viho, Algorithms on graphs, 40 hours, ISTIC Université de Rennes, France.
- Bachelor L3: César Viho, Linux commands/scripts and C Programming, 64 hours, ISTIC Université de Rennes, France.
- Bachelor L2: César Viho, Network basics and main protocols, 32 hours, ISTIC Université de Rennes, France.
- Bachelor L3: Yassine Hadjadj-Aoul, Basics in networking (RES & TCP), 40 hours, Esir/Université de Rennes, France.
- Master, 2nd year: Yassine Hadjadj-Aoul, Scalable Network Infrastructure (SNI), 20 hours, The Research in Computer Science (SIF) master and EIT DigitalMaster/Université de Rennes, France.
- Master, 2nd year: Yassine Hadjadj-Aoul, Multimedia streaming over IP (MMR), 40 hours, Esir/Université de Rennes, France.
- Master, 2nd year: Yassine Hadjadj-Aoul,Multimedia services in IP networks (RSM), 30 hours, Esir/Université de Rennes, France.
- Master, 2nd year: Yassine Hadjadj-Aoul, Software Defined Networks, 20 hours, Istic/Université de Rennes, France.
- Master, 2nd year: Yassine Hadjadj-Aoul, Video streaming over IP, 20 hours, Istic/Université de Rennes, France.
- Master, 2nd year: Soraya Ait Chellouche, Voice over IP (MMR), 15 hours, Esir-Université de Rennes, France.
- Master, 1st year: Soraya Ait Chellouche, IPv6, 15 hours, Esir-Université de Rennes, France.
- Master, 2nd year: Soraya Ait Chellouche, Network security, 32 hours, ISTIC-Université de Rennes, France.
- Master, 2nd year: Soraya Ait Chellouche, Carrier Networks, 20 hours, ISTIC-Université de Rennes, France.
- Bachelor L3: Soraya Ait Chellouche, Network services, 9h, ISTIC-Université de Rennes, France.
- Bachelor L2: Soraya Ait Chellouche, Network fundamentals and main protocols, 12h, ISTIC/Université de Rennes, France.

- Bachelor L3 (CPD) : Soraya Ait Chellouche, Computer networks fundamentals, 39 hours, Continuing Professional Development (CPD),ISTIC-Université de Rennes/École des Transmissions, du Numérique et du Cyber (ETNC), France
- Bachelor L3 (CPD) : Soraya Ait Chellouche, Linux fundamentals and Network services, 40 hours, Continuing Professional Development (CPD),ISTIC-Université de Rennes/École des Transmissions, du Numérique et du Cyber (ETNC), France.
- Bachelor L3 (CPD) : Soraya Ait Chellouche, Network security, 98 hours, Continuing Professional Development (CPD),ISTIC-Université de Rennes/École des Transmissions, du Numérique et du Cyber (ETNC), France.
- Bachelor L3 : Sofiene Jelassi, Advanced Programming, 72 hours, ISTIC/Université de Rennes, France.
- Bachelor L3 : Sofiene Jelassi, Initiation to Java Programming, 12 hours, ISTIC/Université de Rennes, France.
- Bachelor L1 : Sofiene Jelassi, Algorithm Complexity, 27 hours, ISTIC/Université de Rennes, France.
- Bachelor L3 MIAGE : Sofiene Jelassi, Networks, 21 hours in collaboration with University of Cocody-Abidjan, ISTIC/Université de Rennes, France.
- Master, 2nd year : Sofiene Jelassi, VET, 21 hours in collaboration, ISTIC/Université de Rennes, France.
- Master, 1st year : Sofiene Jelassi, PROJET, 24 hours in collaboration, ISTIC/Université de Rennes, France.
- Bachelor L3: Mouloud Atmani, Object Oriented Programming, 52 hours, ESIR/Université de Rennes, France.
- Bachelor L3: Mouloud Atmani, Network and system administration, 35 hours, ESIR/Université de Rennes, France.
- Bachelor L3: Mouloud Atmani, Operating systems, 20 hours, ESIR/Université de Rennes, France.
- Master, 1st: Mouloud Atmani, Network and hardware security, 17 hours, ESIR/Université de Rennes, France.

#### 11.2.2 Supervision

- Yassine Hadjadj-Aoul co-supervised the PhD of Zahraa El Attar, “Network Function Virtualization and Slice Monitoring”, defended in 2025.
- Yassine Hadjadj-Aoul and Gerardo Rubino co-supervised the PhD of Abdelmounaim Bouroudi, “Network traffic classification for identifying multi-activity situations in home environments”, defended in 2025.
- César Viho and Yassine Hadjadj-Aoul co-supervised the PhD of Ahcene Boumhand, “Multi-Task Learning for Home Context Discovery”, CIFRE thesis with Orange, defended in 2025.
- César Viho, Yassine Hadjadj-Aoul and Soraya Aït Chellouche co-supervise the PhD of Wilem Lamdani, “Massive IoT Accesses over Converged Terrestrial-Satellite Networks”, Université de Rennes thesis , from 2023.
- Yassine Hadjadj-Aoul and Soraya Aït Chellouche co-supervise the PhD of Parsa Rajabzadeh, “IA/ML driven safe resource management in 6G with distributed decision making", CIFRE Thesis with Nokia Bell Labs, from 2023.
- Yassine Hadjadj-Aoul supervises the PhD of Lucas Taucoory, "Sustainable AI Integration in 6G Networks: Energy Efficiency and Environmental Impact Optimization", CIFRE Thesis with Nokia Bell Labs, from 2025.

- Maël Le Treust co-supervizes the post-doc Olivier Massicot at IRISA with Giulia Cervia IMT Lille, from 1st Septembre 2025 to 31th August 2027.
- Maël Le Treust co-supervizes the PhD of Mengyuan Zhao at KTH with Tobias Oechtering KTH Stockholm, from 1st June 2023 to 31th May 2027.
- Bruno Sericola and Sofiene Jelassi co-supervise the PhD of Hyun Joon Yoo entitled “Energy-metering and its reduction in a video CDN over post-5G networks", University of Rennes, from 1st December 2025.
- Bruno Tuffin and Sofiene Jelassi co-supervise the PhD of Etienne Faivre D’Arcier entitled “UX-Centric Adaptation of Multi-User Real-Time XR Applications Over Wireless Network", Cifre thesis with InterDigital, from 2025.
- Bruno Tuffin co-supervises the PhD of Burak Kara “Vers une distribution verte de la vidéo : modélisation évaluation et régulation" CIFRE thesis with Synamedia, from March 2023.
- Patrick Maillé co-supervises the PhD of Benedicte Kongo on societal, environmental, and economic impacts of digital infrastructures, CIFRE thesis with Orange.
- Patrick Maillé and Bruno Tuffin co-supervise the PhD of Orland-Medy Saizonou “Towards an efficient economic orchestration of 5G and beyond networks", Inria, from November 2023.

#### 11.2.3 Juries

- César Viho served as Examinator for the PhD jury of Sofiane MESSAOUDI with Adlen Ksentini and Chistian Bonnet in EURECOM, Nice, March 2025.
- Maël Le Treust served as reviewer for the PhD of Reza Deylam-Salehi with Derya Malak and David Gesbert in EURECOM, Nice, December 2025.

# 12 Scientific production

## 12.1 Publications of the year

**International journals**

[1] R. Badouard, I. Lyubareva, P. Maillé and B. Tuffin. ‘An inquiry into Search Engine Neutrality: the case of movements against police violence in France and the U.S.’ In: *Information and Software Technology* 189 (Jan. 2026), p. 107925. DOI: 10.1016/j.infsof.2025.107925. URL: https://inria.hal.science/hal-04690241 (cit. on p. 12).

[2] S. Barick and C. Singhal. ‘UAV-Assisted MEC Architecture for Collaborative Task Offloading in Urban IoT Environment’. In: *IEEE Transactions on Network and Service Management* 22.1 (Feb. 2025), pp. 732–743. DOI: 10.1109/TNSM.2025.3535094. URL: https://inria.hal.science/hal-05449028 (cit. on p. 14).

[3] H. Cancela, L. Murray and G. Rubino. ‘Solving implementation issues of Permutation Monte Carlo in different network reliability contexts’. In: *CLEI Electronic Journal.* 28.3 (16th May 2025). DOI: 10.19153/cleiej.28.3.8. URL: https://inria.hal.science/hal-05451049 (cit. on p. 16).

[4] F. Castella and B. Sericola. ‘Hitting times on the lollipop graph’. In: *Probability in the Engineering and Informational Sciences* 39.4 (2025), pp. 486–519. URL: https://inria.hal.science/hal-05423122 (cit. on p. 16).

[5] F. Castella and B. Sericola. ‘Random Walk in the Complete Graph : Hitting and Cover Times’. In: *Methodology and Computing in Applied Probability* 27.39 (28th Apr. 2025). URL: https://inria.hal.science/hal-05423075 (cit. on p. 17).

[6] N. Charpenay, M. L. Treust and A. Roumy. 'On the Additivity of Optimal Rates for Independent Zero-Error Source and Channel Problems'. In: *IEEE Transactions on Information Theory* (2025), pp. 1–1. DOI: 10.1109/TIT.2025.3639292. URL: https://inria.hal.science/hal-05401169 (cit. on p. 13).

[7] K. Das, D. Sagar Babu, C. Singhal, A. Kumar Dutta and R. Datta. 'A Low-Complexity Modified Pilot-Based Channel Estimation Method for IEEE 802.22 Systems with Performance–Efficiency Trade-off'. In: *IETE Technical Review* 42.6 (6th Oct. 2025), pp. 740–762. DOI: 10.1080/02564602.2025.2563613. URL: https://inria.hal.science/hal-05449039 (cit. on p. 19).

[8] M. Ghosh and C. Singhal. 'A review on machine learning based user-centric multimedia streaming techniques'. In: *Computer Communications* 231 (Feb. 2025), p. 108011. DOI: 10.1016/j.comcom.2024.108011. URL: https://inria.hal.science/hal-05449003 (cit. on p. 19).

[9] C. Singhal, Y. Wu, F. Malandrino, S. G. L. Contreras, M. Levorato and C. F. Chiasserini. 'Resource-Efficient Sensor Fusion at the Edge via System-Wide Dynamic Gated Neural Networks'. In: *IEEE Transactions on Mobile Computing* 24.12 (Dec. 2025), pp. 13243–13257. DOI: 10.1109/TMC.2025.3586882. URL: https://inria.hal.science/hal-05448895 (cit. on p. 19).

[10] C. Singhal, Y. Wu, F. Malandrino, M. Levorato and C. F. Chiasserini. 'Distributing Inference Tasks Over Interconnected Systems Through Dynamic DNNs'. In: *IEEE Transactions on Networking* 33.4 (Aug. 2025), pp. 1717–1730. DOI: 10.1109/TON.2025.3543848. URL: https://inria.hal.science/hal-05448952 (cit. on p. 19).

**Invited conferences**

[11] G. Rubino. 'Connecting irreducible and absorbing Markov chains with applications'. In: JMM 2025 - Joint Mathematical Meeting of the American Mathematical Society. San Francisco CA, United States, 2025. URL: https://inria.hal.science/hal-05451109 (cit. on p. 16).

[12] G. Rubino. 'Evaluation of metrics defined in the initial transient phase for Markovian queues'. In: AMS 2025 - Fall Eastern Sectional Meeting. Virtual conference, United States, 9th Jan. 2025. URL: https://inria.hal.science/hal-05451099 (cit. on p. 16).

**International peer-reviewed conferences**

[13] A. Bouroudi, A. Outtagarts and Y. Hadjadj-Aoul. 'GNN-Based Multi-Agent DRL for Energy-Efficient Multi-Domain 6G Resource Orchestration'. In: GLOBECOM 2025 - Annual IEEE Global Communications Conference. Taipei, Taiwan: IEEE, 2025. URL: https://inria.hal.science/hal-05455207 (cit. on p. 18).

[14] E. Fuentes-Juarez, G. Gallegos-Garcia, M. Rivero-Angeles and G. Rubino. 'Packet-Level System Performance of a Lightweight Consensus Cryptographic Protocol in Wireless Body Area Networks'. In: ICBC 2025 - IEEE International Conference on Blockchain and Cryptocurrency. Pisa, Italy: IEEE, 2025, pp. 1–3. DOI: 10.1109/ICBC64466.2025.11114506. URL: https://inria.hal.science/hal-05451059 (cit. on p. 15).

[15] S. Ghandi, C. Barakat and Y. Hadjadj-Aoul. 'On leveraging browser-level measurements for network troubleshooting'. In: MEDITCOM 2025 - Fifth IEEE International Mediterranean Conference on Communications and Networking. Nice, France: IEEE, 2025, pp. 1–6. DOI: 10.1109/meditcom64437.2025.11104452. URL: https://inria.hal.science/hal-05086467 (cit. on p. 15).

[16] S. A. Hamideche, M. L. Alberi Morel, K. Singh and C. Viho. 'Federated Representation Learning for Encrypted Application Type Classification in beyond 5G RAN'. In: CCNC 2025 - IEEE Consumer Communications and Networking Conference. Las Vegas, United States: IEEE, 2025, pp. 1–7. URL: https://hal.science/hal-04771982 (cit. on p. 18).

[17] B. Kara and G. Simon. 'CDN Failure Management in Content Steering Multi-CDN System'. In: MHV 2025 - ACM Mile-High Video. Denver (Colorado, USA), United States: ACM, 18th Feb. 2025, pp. 1–6. DOI: 10.1145/3715675.3715790. URL: https://hal.science/hal-05029466 (cit. on p. 15).

[18] B. Kara, G. Simon, A. B. Demir, A. C. Begen and F. Agboma. 'Beyond Swiping through Short-Form Videos'. In: MHV 2025 - ACM Mile-High Video. Denver CO USA, United States: ACM, 18th Feb. 2025, pp. 13–18. DOI: 10.1145/3715675.3715792. URL: https://hal.science/hal-05029460 (cit. on p. 15).

[19] B. Kara, B. Tuffin and G. Simon. 'Modeling Energy Regulations for CDN Economics'. In: MHV 2025 - ACM Mile-High Video. Denver (Colorado, USA), United States: ACM, 18th Feb. 2025, pp. 69–70. DOI: 10.1145/3715675.3715805. URL: https://hal.science/hal-05029473 (cit. on p. 13).

[20] E. Le Guern-Dall'o, G. Camilleri, R. Féraud, P. Maillé, F. Petit, R. Zorgati, H. Ben Ahmed and A. Blavette. 'Multi-Agent Multi-Armed Bandits: application to EVs smart charging with grid constraints'. In: *SGE 2025*. SGE 2025 - Symposium de Génie Electrique. Toulouse, France, 2025, pp. 1–6. URL: https://hal.science/hal-05148238 (cit. on p. 14).

[21] E. Le Guern-Dall'o, R. Féraud, G. Camilleri, P. Maillé, F. Petit, R. Zorgati, H. B. Ahmed and A. Blavette. 'Multi-Agent Multi-Armed Bandits: application to EVs smart charging with grid constraints'. In: *Proceedings, 2025 IEEE Kiel PowerTech*. PowerTech 2025 - 16th conference, themed Powering the Energy System Transformation. Kiel, Germany: IEEE, 29th June 2025, pp. 1–6. DOI: 10.1109/PowerTech59965.2025.11180603. URL: https://hal.science/hal-05262742 (cit. on p. 14).

[22] P. Maillé and B. Tuffin. 'Impact of Regulation and the Digital Markets Act on Competing Platforms'. In: *Lecture Notes in Computer Science (LNCS)*. NETGCOOP 2024: 11th International Conference on Network Games, Control and Optimization. Vol. 15185. Lille, France: LNCS, Springer Verlag, 21st Jan. 2025. DOI: 10.1007/978-3-031-78600-6_7. URL: https://inria.hal.science/hal-04613560 (cit. on p. 12).

[23] M. K. Nakayama, B. Tuffin and P. L'Ecuyer. 'Central Limit Theorem for a Randomized Quasi-Monte Carlo Estimator of a Smooth Function of Means'. In: WSC 2025 - Winter Simulation Conference. Seattle, United States, 2025, pp. 1–15. URL: https://inria.hal.science/hal-05130057 (cit. on p. 16).

[24] P. Rajabzadeh, A. Outtagarts, Y. Hadjadj-Aoul and S. Ait-Chellouche. 'HERO: Holistic Envisioned Reinforcement Learning Multi-Domain Orchestration with Latent ODE'. In: CCNC 2025 - IEEE Consumer Communications and Networking Conference. Las Vegas, United States: IEEE, 2025, pp. 1–7. URL: https://inria.hal.science/hal-04770768 (cit. on p. 18).

[25] A. Rguez, Y. Hadjadj-Aoul and G. Rubino. 'A GRASP-based approach for Dynamic and Reliable Virtual Network Embedding'. In: GIIS 2025 - Global Information Infrastructure and Networking Symposium. Dubai, United Arab Emirates: IEEE, 2025, pp. 1–6. DOI: 10.1109/GIIS64151.2025.10922063. URL: https://inria.hal.science/hal-05267740 (cit. on p. 19).

[26] A. Rguez, Y. Hadjadj-Aoul and G. Rubino. 'An Enhanced Exploration GRASP-Based Algorithm for Virtual Network Embedding'. In: ISNCC 2025 - IEEE International Symposium on Networks, Computers and Communications. Paris, France: IEEE, 2025, pp. 1–8. DOI: 10.1109/ISNCC66965.2025.11250437. URL: https://inria.hal.science/hal-05455202 (cit. on p. 19).

[27] P. Rodriguez-Bocca, D. Kiedanski, G. Pereira, S. Collazo, S. Basterrech and G. Rubino. 'An AutoML Framework using AutoGluonTS for Forecasting Seasonal Extreme Temperatures (Accepted in IJCNN'2025, Wokshop: AI for a Cooler Planet: Tackling Environmental Challenges with Neural Networks): Published in the Workshop "AI for a Cooler Planet: Tackling Environmental Challenges with Neural Networks", part of the International Joint Conference on Neural Networks (IJCNN) 2025'. In: *Proceedings of the Workshop "AI for a Cooler Planet: Tackling Environmental Challenges with Neural Networks", in the International Joint Conference on Neural Networks 2025*. Workshop "AI for a Cooler Planet: Tackling Environmental Challenges with Neural Networks", in the International Joint Conference on Neural Networks (IJCNN) 2025. Roma, Italy: IEEE, 30th June 2025. URL: https://inria.hal.science/hal-05454448 (cit. on p. 19).

[28] O.-M. Saizonou, P. Maillé and B. Tuffin. 'Strategic Bandwidth Pricing and Allocation in a 5G/6G Network Slicing Stackelberg Game'. In: ISNCC 2025 - 12th International Symposium on Networks, Computers and Communications. Paris, France, 24th Aug. 2025, pp. 1–6. URL: https://hal.science/hal-05268398 (cit. on p. 12).

[29] M. Sartori, C. Singhal, N. Roy, D. Brunelli and J. Gross. 'AI and Vision Based Autonomous Navigation of Nano-Drones in Partially-Known Environments'. In: DCOSS-IoT 2025 - 21st International Conference on Distributed Computing in Smart Systems and the Internet of Things. Lucca, Italy: IEEE, 8th May 2025, pp. 307–314. DOI: 10.1109/DCOSS-IoT65416.2025.00058. URL: https://inria.hal.science/hal-05448933 (cit. on p. 19).

[30] C. Singhal and Y. Hadjadj-Aoul. 'Energy-Efficient Dynamic Training and Inference for GNN-Based Network Modeling'. In: WCNC 2025 - IEEE Wireless Communications and Networking Conference. Milan, Italy: IEEE, 2025, pp. 1–6. DOI: 10.1109/WCNC61545.2025.10978470. URL: https://inria.hal.science/hal-05267734 (cit. on p. 18).

[31] L. Taucoory, Y. Hadjadj-Aoul and C. Ghribi. 'Green AI for 6G: Quantization of Neural Networks for Predictive Handover from Theory to Practice'. In: GLOBECOM 2025 - Annual IEEE Global Communications Conference. Taipe, Taiwan, 2025. URL: https://inria.hal.science/hal-05455210 (cit. on p. 17).

[32] G. Terrier, C. Gueguen and Y. Hadjadj-Aoul. 'Optimized Usage of Multi-User Diversity to Enhance Spectral Efficiency in (5G) Wireless Networks'. In: ISNCC 2025 - International Symposium on Networks, Computers and Communications. Paris, France: IEEE, 2025, pp. 1–7. DOI: 10.1109/ISNCC66965.2025.11250421. URL: https://hal.science/hal-05402495 (cit. on p. 14).

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**Conferences without proceedings**

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