RESEARCH CENTRE

Inria Saclay Centre

2024 ACTIVITY REPORT

Project-Team TRIBE

inTeRnet BEyond the usual

DOMAIN

Networks, Systems and Services, Distributed Computing

THEME

Networks and Telecommunications

Inria

Contents

Project-Team TRIBE

Creation of the Project-Team: 2019 June 01

Keywords

Computer sciences and digital sciences

A1.1.2. – Hardware accelerators (GPGPU, FPGA, etc.)
A1.2.1. – Dynamic reconfiguration
A1.2.2. – Supervision
A1.2.3. – Routing
A1.2.4. – QoS, performance evaluation
A1.2.5. – Internet of things
A1.2.6. – Sensor networks
A1.2.7. – Cyber-physical systems
A1.2.8. – Network security
A1.3.2. – Mobile distributed systems
A1.3.3. – Blockchain
A1.3.6. – Fog, Edge
A1.4. – Ubiquitous Systems
A1.6. – Green Computing
A2.3. – Embedded and cyber-physical systems
A2.6.1. – Operating systems
A3.1.1. – Modeling, representation
A3.1.3. – Distributed data
A3.1.8. – Big data (production, storage, transfer)
A3.1.10. – Heterogeneous data
A3.2.2. – Knowledge extraction, cleaning
A3.2.3. – Inference
A3.3.2. – Data mining
A3.3.3. – Big data analysis
A3.4.1. – Supervised learning
A3.4.2. – Unsupervised learning
A3.4.3. – Reinforcement learning
A3.4.6. – Neural networks
A3.4.8. – Deep learning
A4.4. – Security of equipment and software
A4.8. – Privacy-enhancing technologies
A5.11.1. – Human activity analysis and recognition

A7.1. – Algorithms

A7.1.3. – Graph algorithms

A8.1. – Discrete mathematics, combinatorics

A8.3. – Geometry, Topology

A8.6. – Information theory

A8.7. – Graph theory

A8.9. – Performance evaluation

A9.2. – Machine learning

A9.6. – Decision support

A9.7. – AI algorithmics

A9.8. – Reasoning

A9.9. – Distributed AI, Multi-agent

Other research topics and application domains

B4.4. – Energy delivery

B4.4.1. – Smart grids

B4.5. – Energy consumption

B5.8. – Learning and training

B6.2.2. – Radio technology

B6.3.2. – Network protocols

B6.3.3. – Network Management

B6.4. – Internet of things

B6.6. – Embedded systems

B7.2.1. – Smart vehicles

B8.1.2. – Sensor networks for smart buildings

B8.2. – Connected city

B8.3. – Urbanism and urban planning

B9.5.1. – Computer science

1 Team members, visitors, external collaborators

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- Anne Josiane Kouam Djuigne [TU-Berlin, from Feb 2024]
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2 Overall objectives

TRiBE (*"inTeRnet BEyond the Usual"*) was officially created in June 2019. TRiBE belongs to the Inria theme *"Networks and Telecommunications"*. The focus and the evolving directions of TRiBE research contribute, among others, to the priority themes "Digital Security" (as for programming for the Internet of Things) and "Responsible AI and Algorithms" (as for algorithms design, data processing pipelines, green digital twins).
Main goal: *Building on a ombination of protocol design, data learning, modeling, and experimental research, TRiBE's contributions aim to shape smart, unified, and perceptive Internet Edge networks, designed to effectively meet the real demands and purposes of applications, services, and end users, while adapting to the specificities and usability of devices.*

2.1 Projections and emerging challenges

The Internet Edge has evolved significantly over the past decades, transitioning from a small, homogeneous network to a vast Internet of Things (IoT) ecosystem, interconnecting a wide variety of devices, : while supporting a diverse range of services. *We are constantly adapting our focus the new related projections*:

- **Significant IoT Devices Growth:** The number of global IoT connections is expected to rise to nearly 40 billion devices by 2033 (from 16.1 billion in 2023), with a compound annual growth rate (CAGR) of 10%. This includes *substantial growth in short-range and cellular IoT technologies*, driven by expanding use cases in consumer (e.g., smart homes, wearable devices), industrial, and urban environments (IoT Analytics; Ericsson IoT Report). Meanwhile, *hundreds of billions of low-power microcontrollers* worldwide are in use daily [86], and tens of billions ship yearly [85]. These trends bring huge opportunities on the one hand, and on the other hand *new cybersecurity threats* are a major concern [67].

- **Mobile Traffic Growth:** Mobile traffic is projected to *grow exponentially, driven by high-bandwidth applications (e.g., video streaming, XR) and 5G adoption.* Smartphones account for 95% of mobile data traffic by 2026, fueled by advancements like video codecs, higher screen resolutions, and AI-driven personalized content. Autonomous vehicles are emerging as a significant source of traffic demand, relying on HD maps, passenger entertainment systems, and vehicle diagnostics, continuous data exchange with cloud servers, HD mapping services, and vehicle-to-everything (V2X) communication (Ericsson Mobility Report, Cisco Report, V2X White Paper).

- **5G and Future of 6G:** 5G-enabled IoT devices are key to delivering high-speed, low-latency applications at the network edge. By 2033, 5.5 billion cellular connections (*including mMTC, as NB-IoT and LTE-M, and RedCap/eRedCap*) are expected, including 1.1 billion full 5G NR connections. In Europe, 87% of mobile users will have 5G coverage by 2030. Looking ahead, 6G aims to *integrate enhanced mobile broadband with AI*, driving innovations in industries like smart cities and autonomous transportation (N-iX, IEEEComSoc Tech. Blog, GSMA Report).

- **Edge Computing and Device Specificity:** Edge computing, combined with IoT and AI, is revolutionizing many sectors (e.g., smart industries, intelligent transportation systems, healthcare, smart cities, industrial automation). By processing data closer to devices, edge computing reduces latency and improves efficiency. By 2030, 75% of enterprise-generated data is expected to be created and processed outside traditional data centers, *highlighting the critical role of Internet edge networks and devices.* However, while the edge is critical for real-time, localized tasks, *the cloud remains essential for large-scale data aggregation, advanced AI model training, and global coordination. We are convinced that, together, edge and cloud architectures enable a balanced approach, combining real-time decision-making with scalable insights to support the growing demands of IoT ecosystems* ([69], N-iX, IDC Report, Transforma Insights).

These projections emphasize the growing need for smarter, more efficient networking and IoT solutions, along with adaptive edge computing, to address the increase in IoT connections, the rising impact of mobile networking connectivity, and the resulting increase in data volumes.

2.2 Team vision and approach

We firmly believe the success of the IoT lies in: (i) the *network design choices* determining how devices are integrated, (ii) the *intelligence of algorithms, protocols, and services* accurately interpreting demands and purposes, and (iii) the *adaptability of the device-edge-core communication loop* enabling rapid responses and efficient network management. Hence, we base our approach on the combination of data or communication learning, modeling, algorithms/protocols design, and experimental research, while meeting the requirements and challenges brought by the IoT to the edge of the Internet. Therefore, our is organized around the following research directions:

- **Technologies for accommodating low-end IoT devices (resource-limited IoTs):** We tackle the optimization, simplification, and unification requirements imposed by the heterogeneity and low capabilities of low-end IoT devices. This brings the necessity to deal with limitations and to propose solutions close to hardware and software specifications.

- **Technologies for leveraging high-end IoT devices' advent (smart IoTs):** We focus on learning the behaviors of high-end IoT devices, the smart devices. The idea is to take advantage of the "*how in the spatiotemporal scale*" and the "*for what purpose*" these devices use the network resources. This brings the human element into play, in which dynamics and uncertainties are shaping the way their devices interact with the edge of the Internet and, consequently, request and consume network resources and services.

- **Technologies for edge-core network interaction:** This element closes the *network* $\leftrightarrow$ *usability* $\leftrightarrow$ *device* $\leftrightarrow$ *network* loop" by bringing solutions supporting functions and communication between IoT devices and the core of the Internet while putting into practice the solutions proposed in the two previous directions.

Through these three research axes, the team places its efforts on the three main elements composing the ecosystem of IoT devices: (1) the device itself, (2) their usability, and (3) their network context. Together, these research axes will contribute to our vision toward a *Smart, Unified, and Tactful Internet edge skilled for answering the application, services, or end-users' purposes.*

3 Research program

Following up on the effort initiated by the team members during the last few years and building on an approach combining protocol design, data analytics, and experimental research, we propose a research program organized around three closely related objectives that are briefly described in the following.

- [**Axis 1**] **Technologies for accommodating low-end IoT devices:** The IoT connects billions of low-end devices to the Internet, and billions more are projected, significantly increasing machine-to-machine communication. Unlike high-end devices based on *microprocessors*, low-end IoT devices are based on *microcontrollers*, highly resource-constrained in energy, memory, and computational power. These characteristics prevent them from running standard platforms like Linux or complex protocol stacks based on TCP/IP. Addressing these challenges requires: (i) **optimized communication protocols** that align with evolving radio technologies and device constraints; (ii) **tailored software platforms** offering modular updates, high-level programming, machine learning support and energy efficiency features; (iii) **unification of fragmented low-end IoT technologies** to ensure seamless integration with core and edge networks, and (iv) **low-footprint cybersecurity mechanisms** which enable such devices to take part in cyberphysical, ditributed systems without becoming the weakest link. To support these advancements, we propose targeted research activities addressing wireless communication evolution for constrained IoT devices.

- [**Axis 2**] **Technologies for leveraging high-end IoT devices' advents:** Our reliance on pervasive connectivity and extensive usability of high-end IoT devices allows capturing human life patterns of end-users printed in the digital world. Thus, human dynamics directly influence how resources, services, and infrastructures are utilized at the Internet Edge, shaping *where, when, how, and what* is accessed. Consequently, studying end-users' behavioral patterns (e.g., mobility, content preferences) and incorporating the inherent heterogeneity and unpredictability into networking solutions is critical. This challenge underpins Axis 2, which aims to establish a *tactful networking design practice* – enabling networks to observe, interpret, and adapt dynamically to the daily life features of high-end IoT devices' end-users. The research activities of this axis focus on three main topics: **(i) extracting high-end IoT footprints in networking data**, while enforcing data representativeness and trajectories inference; **(ii) end-users' patterns understanding at the Internet edge**, for profiling and prediction of individual spatio-temporal usability of the Internet edge, emphasizing novelty- and routine-like mobility modeling and urban flow understanding; and **(iii) addressing vulnerability and security concerns** linked to end-users' patterns in digital datasets.

- [**Axis 3**] **Articulating the IoT edge with the core of the network:** The edge acts as the interface between IoT devices and the core network, addressing interoperability, heterogeneity, and mobility. It supports several intermediary functions when connecting devices to the Internet. Our work in this axis, more so than in the other axis, proceeds on three distinct levels: the first level is the application area (e.g., UAV, V2X, generic Edge/Cloud), the second level is the underlying technologies (e.g., blockchains, information-centric networking), and the third level is the specific methods and techniques (e.g., AI/ML, RL, federated learning, split computing, offloading). Each study generally combines two or three of these levels. We present them according to the level we emphasize:, heterogeneity, and mobility challenges (i) **Decentralized network mechanisms and architectures** (application area: V2X), (ii) **Machine Learning enhanced network protocols and classical network optimization** (methods and techniques), (iii) **Edge network offloading** (methods and techniques), (iv) **Security of the edge/core compound including IoT deployments** technologies).

4 Application domains

Hereafter, we describe the general 1) domains of research of TRiBE and 2) the contexts and applications where our solutions are applied.

- **Research domains:** Our research spans a range of domains, including computer science, mobile wireless networks, Internet of Things (IoT), Tactile Internet, human mobility analytics and prediction, edge-smart resource allocation, IoT software design, social networks, energy-saving technologies, and mobility-aware networking solutions.
- **Tactile Internet:** As the next evolution of the IoT, the Tactile Internet focuses on applications combining ultra-low latency with extremely high availability, reliability, and security. These applications demand smart interactions between individuals and devices, as well as device-to-device communication, enabling real-time and reliable interactions for industrial, societal, and business use cases. Examples of applications include automation and smart transportation, 3D and educational games, and x-reality applications and services. Our solutions aim to: (i) introduce intelligence and quasi-in-time adaptivity (accounting for individuals' behaviors, IoT limitations, and the context of services and environments) in networking's resource allocation, management, and usability, and (ii) contribute to achieving the goals of the Tactile Internet.
- **IoT twins:** The rise of IoT is driving the emergence of digital twins—digital copies of complex systems—operable via 5G or next-generation networks. Digital twins provide real-time information on working/leisure areas, traffic, weather conditions, air quality, and more, for a city, region, or even an entire country. These highly distributed systems require robust and reactive blockchain mechanisms to manage massive data flows from millions of sensors transmitting at high frequency. Our solutions in **IoT-massive edge applications, analytic learning theory, and frugal AI** are designed to support the development of such systems. Additionally, digital twins for traffic, transportation, and geographic visitation will require insights into population mobility and space usage. Our solutions in mobility understanding, profiling, and simulation are well-suited to advance these applications.
- **Urban planning and disaster management applications:** Our research provides critical insights for applications in urban planning and disaster management. For instance, topics such as *SafeCityMap: From spatiotemporal mobility of our society to COVID propagation understanding* and *Geometry of virus exposure* (detailed in the "New Results" section) exemplify our work. Broadly speaking, mobility analytics from these projects enhance understanding of urban space usage and support: (i) Epidemic prevention and disaster response; (ii) Urban traffic management and mobility prediction algorithms; (iii) Provision of energy-efficient, cost-effective network infrastructures tailored to changing mobility patterns. Our tools and investigations also enable the study of spatiotemporal activity in geographic areas (e.g., visitation rates and patterns), providing insights into the socio-economic impacts on residential or activity-based zones—particularly during situations like lockdown periods.
- Additional applications influenced by our research are discussed in the next section on Social and Environmental Responsibility.

5 Social and environmental responsibility

5.1 Footprint of research activities

We believe our research can benefit society and the environment because:

- The Internet of Things (IoT) is set to dramatically increase the number of connected devices, potentially raising network power consumption and environmental impact. However, many IoT applications address environmental management by monitoring and resolving critical issues. Most devices are low-power wireless systems, often solar-powered. *Our research focuses on optimizing efficient low-end networks and minimizing the costs of creating sensor field digital twins through green blockchain designs.*

- Smart devices, inheriting user dynamics and decision-making, introduce uncertainties in predicting where and when network resources are needed. The common Internet response has been over-provisioning resources to manage this instability, which also exacerbates energy inefficiency. However, in a predominantly mobile Internet, such practices inflate energy consumption, becoming both costly and unsustainable, necessitating a strategic re-evaluation. *Our research fosters just-in-time networking resource usability.*

- The European Commission's Sustainable and Smart Mobility Strategy (2020) underscores that achieving the Green Deal's goals hinges on creating a sustainable transport system. This transformative vision reshapes how we view transport usability and availability, human mobility, and its interaction with spatial dynamics, emphasizing the need to understand mobility behavior and its drivers of change. *Our research emphasizes such aspects.*

The previous assertions naturally guide our research and envisioned outcomes. TRiBE's research contributes to environmental and societal responsibilities in the following ways:

- TRiBE research is targeting a network intelligence much closer to end-users – and consequently, to the edge of the Internet. In this sense, edge intelligence (i.e., learning, reasoning, and decision-making) provides distributed autonomy, replacing the classical centralized structures. TRiBE results thus, contribute to (1) smartly using networking resources, (2) using a lower amount of aggregated power in dispersed locations, and (3) avoiding the energy consumption related to the transmission of information back and forth to the Internet core. This conviction is the common thread in **the suitable by-design solutions of the 2nd and 3rd TRiBE's axis/focus**, which will naturally contribute to the new energy-efficient architectural evolution of the Internet.

- TRiBE research pursues the conviction that methods allowing to smartly and efficiently allocate/use resources (of devices and the network) at the Internet edge are energy-friendly and contribute to the IT sector's electricity needs. This conviction is also the common thread behind **the 2nd and 3rd TRiBE's axis**.

- Besides, the understanding of the way carried high-end IoT devices move and interact with one another (i.e., related to axis 2 and 3 of TRiBE) has the potential to impact **epidemiology studies, urbanization investigation, and Internet provisioning** (e.g., in the successful comprehension of the spread of epidemics or of the population; in urban planning; in intelligent transportation systems in smart cities; for urban space management; or in more suitable-for-devices resource allocation. The SafeCityMap [70] and Ariadne Covid Inria-Covid projects carried by members of the team reinforce such assertion. In particular, the SafeCityMap project investigates the impact of the 1st, 2nd, and 3rd lockdown on the regular mobility habits of the Paris population. Results of such investigations are posted in the interactive SafeCityMap website. Besides, our recent investigation shows a natural correlation between pollution indicators and SafeCityMap results describing mobility preferences and landscape usability in Paris: Indicators **having the potential to impact society and population health**.

- In the **1st TRiBE's axis**, TRiBE goals also relate to the provision of optimized communication protocols and software solutions designed to fit the stark specificities of low-end IoT devices while taking into account radio technology evolution. The motivation here is to efficiently use and manage the billions of low-end devices expected to (i) gradually connect to and (2) drastically increase the communication, and consequently, the energy consumption, on the Internet. TRiBE's 1st research axis pursues the conviction that the smart accommodation of low-end IoT devices' related solutions will contribute to energy efficiency at the Internet edge. In a part of our research work, we focus on constrained devices (constrained in processing power and energy) and provide efficient algorithms in computation and communication reduction, both being translated into energy savings, reducing, thus, the energy footprint of the IoT.

- A sizable part of our research activities is carried on top of open-source software that we develop, and especially the **open source software platform RIOT**, an OS for the Internet of Things, targeting

low-power embedded devices based on microcontrollers (i.e., **related to axis 1 of TRiBE**). In this way, research and developments that improve energy efficiency directly on the RIOT OS are made readily available to IoT practitioners. Several TRiBE members contribute actively to this platform, around which a large international community has snowballed. In this way, research and developments that improve energy efficiency are made readily available to IoT practitioners, e.g., through RIOT or other software in the ecosystem.

5.2 Impact of research results

Ethics: We handle ethical issues in our research as developed in Scientific integrity and open science practices (see subsections 4.1 and 4.2). **Socio-economic impact:**

- As a result of TRiBE engagement in EU environment and green priorities, the team is strongly involved in four projects of two national research actions (**PEPR**): (1) the MOBIDEC (i.e., *Digitalisation and Decarbonisation of Mobilities*) focusing on the digital and carbon neutrality of mobility and (2) the *5G and Network of Future* aiming the development of 5G and 6G while assessing their environmental impacts. Both PEPRs and, consequently, the contributions of the team on such actions will contribute to make research impacting the environment and society while ensuring the security of transmitted data and privacy compliance of treated mobility traces. This engagement is **present in all the three TRiBE's research axes.**

- When privacy concerns are identified, TRiBE has dedicated efforts in designing solutions to ensure anonymization and/or fraud detection of wireless networks' datasets. Related to the anonymization concern, we point out important privacy-related flaws in current wireless communication standards [77]. Our related designed solutions highlight the possibility to efficiently (i) identify devices associated with randomized addresses and (ii) reconstruct their trajectories only based on signal measurements (cf. the PhD thesis of Abhishek Kumar Mishra [82]).

- Besides, the team contributions on cellular fraud detection bring a deep understanding of the evolution of frauds of SIMBox type and on the vulnerabilities of current related detection literature [75] (cf. the PhD thesis of A. J. Kouam). By highlighting flaws and vulnerabilities of literature, TRiBE brings contributions that have a potential societal and economic impact.

- Other contributions such as [83, 78, 68, 65] demostrate the engagement of the team in **enforcing the carbon neutrality and the green management of mobility**.

- Last but not least, another means for our research results to have an impact is through **contributions to standardization** (including IETF): TRiBE members co-author standards and help to define and specify efficient protocols and their optimization.

General audience: We have also been intervening in the public debate and fostering science disseminaiton:

- A. C. Viana and N. Achir have participated of the *"L'esprit sorcier"* channel seeking to elucidate scientific inquiries with the input of experts from prominent French public research institutions. The scientific context was *"Human mobility and its impact on network ressources"* (Nov. 2023), where the ANR MITIK project was also presented.

- E. Baccelli talk on low-power IoT cybersecurity and future-proofing RIOT at Open Source Experience and SIDO Paris, 2024 (VivaTech, June 2024).

- Anne Josiane Kouam Djuigne, Abhishek Mishrak, and C. Adjih have welcomed and have presented to a group of high-school students insights on research careers, research topics on cellular SIMBox fraud, IoT concepts, and programming.

6 Highlights of the year

Aline C. Viana : (**1**) Announced as one "2024 N2Women: Stars in Networking and Communications" by N2Women community an ACM SIGMOBILE program. (**2**) Recognized as ACM Senior Member 2024 for her technical leadership, and technical and professional accomplishments;

The team hosted and co-organized the Indo-French Seminar "6G Wireless Networks: Challenges and Opportunities", October 9 to October 11, 2024, and funded by CEFIPRA and Inria. It brought together researchers working in India and France to present and discuss cutting-edge advancements in wireless communication technologies, focusing on the future of 5G and 6G networks. This was also in the context of the associated team MAGICO

7 New software, platforms, open data

Our team emphasizes real-world implementation of research contributions, ensuring theoretical findings are validated through practical development. Each project includes a functional prototype, framework, or software tool, developed iteratively alongside research advancements. Committed to privacy and ethics, the team ensures developed software adhere to these principles. Following an open-source approach, all software and frameworks are made publicly available under open-source licenses whenever possible. Moreover, even though part of our work involves collecting or handling private data, we are committed to ensuring that our tools respect privacy and adhere to ethical standards.

7.1 New software

7.1.1 RIOT

Name: RIOT

Keywords: Internet of things, Operating system, Sensors, Iot, Wireless Sensor Networks, Internet protocols

Scientific Description: While requiring as low as 1,5kB of RAM and 5kB or ROM, RIOT offers real time and energy efficiency capabilities, as well as a single API (partially POSIX compliant) across heterogeneous 8-bit, 16-bit and 32-bit low-hardware. This API is developer-friendly in that it enables multi-threading, standard C and C++ application programming and the use of standard debugging tools (which was not possible so far for embedded programming). On top of this, RIOT includes several network stacks, such as a standard IPv6/6LoWPAN stack and a information-centric network stack (based on CCN).

Functional Description: RIOT is an Open Source operating system that provides standard protocols for embedded systems. RIOT allows, for example, the development of applications that collect sensor data and transmit it to a central node (e.g. a server). This data can then be used for smart energy management for instance.

RIOT is specially designed for embedded systems, which are strongly constrained in memory and energy. Further, RIOT can easily be ported to different hardware devices and follows the latest evolution of IP standards.

RIOT applications can readily be tested in the FIT IoT-Lab, which provides a large-scale infrastructure facility with 3000 nodes for testing remotely small wireless devices.

News of the Year: 4 releases in 2024: RIOT 2024.01, RIOT 2024.04, RIOT 2024.07, RIOT 2024.10,

Statistics for 2024 (lower bounds): 708+ pull-requests merged, 1534+ commits merged, Contributions from $\tilde{5}$0 contributors worldwide, 292696+ lines of code added, 40754+ lines removed.

Some of the (numerous) enhancements: - AVR-8 now has power management, - the GNRC border router application supports ZEP topology, - SUIT software update now accept firmwares signed with different keys, - RIOT can run natively on 64-bit Linux / x86_64, - added support for Arduino

Nano 33 BLE Sense and various boards with Ethernet plugs, - first steps towards enabling RIOT support of new Microchip SAM MCUs, - the PSA Crypto API implementation in RIOT now supports persistent key storage and additional hashing algorithms - ... among many other improvements ...

URL: http://www.riot-os.org

Contact: Emmanuel Baccelli

Participants: Emmanuel Baccelli, Koen Zandberg, Oliver Hahm, Francois-Xavier Molina, Alexandre Abadie

Partners: Freie Universität Berlin, University of Hamburg

7.1.2 FraudZen

Keywords: Fraud detection, SIMBox fraud, LTE, Simulator

Scientific Description: FraudZen is an open-source simulator of the activities (traffic and mobility) and interactions of legitimate and SIMBox fraudulent users, on the top of a realistic cellular network infrastructure. From input models of legitimate and fraudulent behaviors, FraudZen generates CDRs datasets.

Functional Description: FraudZen is an open-source simulator of SIMBox fraud strategies in LTE networks. It is designed to tackle the lack of fraudulent and up-to-date CDRs, which is the ground truth required for efficient SIMBox fraud mitigation.

FraudZen reproduces the realistic cellular network architecture of a SIMBox fraud's target area and simulates the network usage and interactions of legitimate and SIMBox fraudulent users on top of this architecture. FraudZen's resulting CDRs convey users' communication behavior at individual fine-grained precision. Researchers and mobile operators can use this tool to (i) inject fraudulent traffic to their CDRs and check the validity of their designed solutions, (ii) analyze the impact of the so-farunreachable SIMBox ecosystem, i.e., SIMBox architecture and fraud parameters, (iii) reproduce and explore off-net fraud mechanisms, and (iv) design and investigate new fraud schemes. The full control and flexibility related to the simulation environment guarantee complete and large fraudulent CDRs ground truth for detection models' training. Moreover, FraudZen allows anticipating the fraud evolution, freeing research from the past/current fraud capabilities and allowing the incorporation of not-yet-existing SIMBox functionalities in foresight.

News of the Year: - Anne Josiane Kouam organized the 1st FraudZen Hackathon (https://aj-kouam.github.io/fraudzen-hackathon/) at the University of Yaounde 1 (UY1) in Cameroon, in the context of the Berlin University Alliance (BUA) project entitled "Leveraging AI for Detecting SIMBox Fraud in Mobile Networks" she led.

- The hackathon lasts 4 weeks (November 2024) and focuses on developing AI-based techniques to detect SIMBox fraud in mobile networks, addressing a significant challenge in telecom security. The initiative also fosters international research cooperation and knowledge exchange between Berlin and Cameroon.

- The ongoing projects related to fraud detection and network security when maturated, will be integrated into a future version of the simulator.

URL: https://gitlab.inria.fr/simbox-fraud-mitigation/fraudzen

Publications: hal-03838853, hal-04543435

Contact: Aline Carneiro Viana

7.1.3 MITIK-MGMT

Name: MITIK Data Collector Management Tools

Keywords: Wi-Fi, Infrastructure software, Mobile Crowdsensing

Scientific Description: MITIK-MGMT is an open-source management tool developed as part of the MITIK project and aims to automate the configuration process and management of experiments using WiFi collectors offered in MITIK. The supported functions are: - Provide a tool that allows the simultaneous configuration of multiple collectors. - Centralized management of several collectors (synchronization, raw data capture, data transfer, and processing...). - Configuration of parameters and execution of MITIK project modules.

Functional Description: The objective of the MITIK project is to carry out non-intrusive passive measurements to analyze the mobility of users through contacts during their travels. The objective is to use probe-request packets coming from mobile devices using WiFi-type wireless communications. MITIK-MGMT is a management tool developed as part of the MITIK project and enables, through a "sniffer manager," the automated setup and management of practical experiments using WiFi collectors.

News of the Year: - Maturated version of the MITIK-MGMT tool, with revisions of documentation and parametrization. - The code was also recently deposited as open-source with GPLv3.0-or-later license. - The code is registered at Software Heritage as referred in document hal-04814847 in HAL. - The following HAL report provides configuration and usability instructions: https://inria.hal.science/hal-04818320v1 - For dependencies among MITIK tools, refer to MITIK-GUIDE (https://gitlab.inria.fr/mitik/mitik-guide)

URL: https://gitlab.inria.fr/mitik/measurement-management/mitik-mgmt

Publications: hal-04568193, hal-04814847

Contact: Nadjib Achir

Participants: Aline Carneiro Viana, Nadjib Achir, Fernando Molano Ortiz, Fernando Dias De Mello Silva

7.1.4 MITIK-SENS

Name: Privacy-preserving WiFi Sniffer tool

Keywords: Wi-Fi, Privacy

Scientific Description: Public wifi (IEEE 802.11) networks are an abundant data source that may serve different applications such as epidemic tracking and prevention, disaster response, crowdsensing, or ubiquitous urban services. Nevertheless, collecting and exploiting such data brings many privacy liabilities, considering that each transmitted frame has the MAC address (a unique device identifier) of the corresponding personal device, also considered sensitive information. Literature has shown that the MAC randomization performed by phone manufacturers is insufficient to protect devices' identification. Data obfuscation is a promising solution to avoid storing advertised identifiers of devices and prevent attackers from acquiring sensitive data. Obfuscating such identifiers while also being able to differentiate frames sent by different devices poses a significant challenge for frame capturing by low-resource IoT devices in real time. Since no popular off-the-shelf sniffer (wireshark or tcpdump, etc..) allows for on-the-fly obfuscation, we build a new custom-made sniffer module **MITIK-SENS** capable of on-the-fly obfuscating (hash and truncate) the required data needed of each wifi frame to protect user privacy.

Functional Description: Privacy-preserving WiFi Sniffer tool with on-the-fly MAC Address Obfuscation.

News of the Year: - 1st version of the MITIK-SENS tool, with revisions of documentation and parametrization. - The code was also recently deposited as open-source with GPLv3.0-or-later license and registered at Software Heritage, as referred in doucment hal-04816385 in HAL. - The following HAL

report provides configuration and usability instructions: https://inria.hal.science/hal-04818079v1 - For dependencies among MITIK tools, refer to MITIK-GUIDE (https://gitlab.inria.fr/mitik/mitik-guide)

URL: https://gitlab.inria.fr/mitik/anonymous-measurement/mitik-sens

Publications: hal-03906600, hal-04568193, hal-04816385

Contact: Fernando Dias De Mello Silva

Participants: Aline Carneiro Viana, Nadjib Achir, Luis Henrique Maciel Kosmalski Costa, Fernando Molano Ortiz, Fernando Dias De Mello Silva, Anne Fladenmuller, Abhishek Mishra

7.1.5 MITIK-LINK

Name: MITIK MAC Address Association

Keywords: Wi-Fi, Probe-requests, MAC address randomization, Frame association

Scientific Description: MITIK-LINK is a tool designed to associate randomized MAC addresses within WiFi network traces gathered from the MITIK-SENS tool.

Functional Description: MITIK-LINK performs the MAC association of randomized MAC addresses used by the same device. This tool models the frame association to resolve MAC conflicts in small intervals. It uses time and frame content-based signatures to resolve and associate MACs inside a conflict. Finally, a logistic regression-based algorithm using the obtained signatures is proposed to associate devices with similar signatures.

News of the Year: - 1st version of the MITIK-LINK tool, with revisions of documentation and parametrization. - The code was also recently deposited as open-source with GPLv3.0-or-later license and registered at Software Heritage, as referred in Document hal-04815312 in HAL. - The following HAL report provides configuration and usability instructions: https://inria.hal.science/hal-04818359v1 - For dependencies among MITIK tools, refer to MITIK-GUIDE (https://gitlab.inria.fr/mitik/mitik-guide)

URL: https://gitlab.inria.fr/mitik/mac-association/mitik-link

Publications: hal-04815312, hal-03298339, hal-04171864, tel-04311364, hal-04568193

Contact: Nadjib Achir

Participants: Abhishek Mishra, Aline Carneiro Viana, Nadjib Achir, Fernando Molano Ortiz

7.1.6 MITIK-TRAJ

Name: MITIK-TRAJ - WiFi devices trajectory inference tool

Keywords: Wi-Fi, Trajectory Generation, Mobility

Scientific Description: MITIK-TRAJ is a tool for trajectory reconstruction of a WiFi mobile terminal. It leverages the signal strength of users' public WiFi probe requests collected from measurements of multiple deployed or sniffers. Characterize and approximate the error in the radial distances between the device and the sniffer. Leverage the error characterization and approximated radial distances to estimate the bounds associated with a device's position. Finally, considering the spatiotemporal bounds of device positions over time, it infers the user's bounded trajectory.

Functional Description: MITIK-TRAJ is a tool for reconstructing the trajectory of equipment from their Wi-Fi traces by introducing the concept of bounded trajectory. The tool considers three significant components: i) Generating observation sets, ii) Characterizing radial-distance estimation errors, and iii) Obtaining bounded trajectories.

News of the Year: - 1st version of the MITIK-TRAJ tool, with revisions of documentation and parametrization. - The code was also recently deposited as open-source with GPLv3.0-or-later license and registered at Software Heritage, as referred in Document hal-04924988 in HAL. - The following HAL report provides configuration and usability instructions: https://inria.hal.science/hal-04925002v1 - For dependencies among MITIK tools, refer to MITIK-GUIDE (https://gitlab.inria.fr/mitik/mitik-guide)

URL: https://gitlab.inria.fr/mitik/trajectory-reconstruction/mitik-traj

Publications: hal-03906579, tel-04311364, hal-04568193, hal-04924988

Contact: Nadjib Achir

Participants: Abhishek Mishra, Aline Carneiro Viana, Nadjib Achir, Fernando Molano Ortiz

7.1.7 MobilityPulse

Name: MobilityPulse - Routine and Novelty-Seeking Behaviors Analysis Framework

Keywords: Mobile phone, Human mobility, Mobility, Behavior modeling, Statistical analysis, Profiling, Prediction, Predictive analytics

Scientific Description: This framework examines routine and exploratory tendencies in human mobility, influencing mobility predictability and practical visit predictions. On the routine side, it extracts the predictability of input datasets and identifies three key mobility features—regularity, stationarity, and diversity—that impact predictability. Additionally, it facilitates the analysis of contextual factors affecting predictability.

From the exploratory perspective, existing mobility research struggles to accurately capture novelties in human movement, where the severity of uncertainty influences prediction accuracy. This framework introduces a two-dimensional mobility model that explicitly accounts for regular and exploratory behaviors. It also enables individuals to be classified into three mobility profiles: Scouters, Routiners, and Regulars. Moreover, we analyze the mobility features of each profile— e.g., regularity, radius of gyration (RoG), stationarity, diversity, maximum displacement, etc — to characterize mobility behavior. Furthermore, the framework comprehensively evaluates how novelty-seeking tendencies affect theoretical and practical mobility predictability.

Functional Description: MobilityPulse suggests focusing on the "heartbeat" or rhythm of human movement, capturing both the regular patterns (routine) and the spikes of activity that represent novelty-seeking behaviors. The framework analyzes the underlying dynamics (related to routine-like mobility) and variations (moments of exploration) in human mobility, much like how a pulse reflects changes in a person's physiological state. Finally, the framework allows the investigation of the predictability of routine-like patterns and the ability to perform predictions while being aware of moments of exploration.

Release Contributions: No functional differences compared to the previous version, but changes related to the documentation.

News of the Year: - A bug on the tessellation of datasets was detected and corrected.

URL: https://gitlab.inria.fr/mobility-framework/mobcomp-framework/MobilityPulse-framework

Publications: hal-03905517, hal-02286128, hal-01367825, hal-04699871, hal-02286080, hal-03360537, hal-03128639, hal-02944150, hal-03444658

Contact: Aline Carneiro Viana

Participants: Aline Carneiro Viana, Licia Amichi, Douglas Do Couto Teixeira, Jussara Marques Almeida, Joao Paulo Esper Spindula, Antonio Alfredo Ferreira Loureiro, Mark Crovella

Partners: Inria, Federal University of Minas Gerais, Boston University

7.1.8 En-WDM

Keywords: Human mobility, Simulation, Statistical modeling

Scientific Description: En-WDM builds upon WDM as its foundational element, enriching its capabilities. Our motivation to use WDM is twofold. First, in contrast to models found in related literature, WDM originality comes from the combination of various mobility aspects present in people's daily lives (e.g., home and workplaces, day periods). Secondly, WDM closely mirrors the distributions of wireless interactions, including inter-contact and contact time, as observed in two real-world measurement experiments (i.e., iMote and Dartmouth), establishing its modeling generality. However, WDM does have limitations in capturing certain nuanced real mobility habits and fine-tuning aspects. En-WDM addresses these constraints by enhancing the model with additional insights from the literature on laws governing human mobility behavior. This includes considerations such as preferential attachment, regular daily behavior, transportation-dependent shortest-path preferences, and, crucially, accounting for uncertainty (novelty-seeking behaviors) and heterogeneity. Specifically, En-WDM assigns to the emulated users: (i) Trajectories that incorporate routine- and exploration-based locations, (ii) Displacement profiles, along with preferential neighborhoods (e.g., residential zones, business districts), (iii) Profiles associated with the maximum distance covered in their displacements and (iv) Fine-grained parameterization tailored to a real-world city (i.e., Helsinki), reproduced with high fidelity.

Functional Description: Domain-wide recognized by their high value in diverse domains, such as sociology, epidemiology, transportations, and networking, the access to human mobility data for research faces multiples challenges, related to its inherently private nature.

To bridge this gap, the En-WDM framework aims the realistic emulation of a population urban mobility in a real-world city map, with users displacements generated according to public sources and describing city planning and transportation information. En-WDM inherits the highly configurable capability of the Opportunistic Network Environment (ONE) simulator. Besides, it enhances the Working Day Mobility model (WDM) of ONE into a more realistic model and generates related human mobility data to the format <Timestamp, userId, lat,lon>.

Release Contributions: No functional differences compared to the previous version, but changes related to the documentation.

News of the Year: - Small addings in documentation and code optimisation.

URL: https://gitlab.inria.fr/simbox-fraud-mitigation/legitimate-mobile-datasets-generation/en-wdm

Contact: Aline Carneiro Viana

7.2 New platforms

Open Experimental IoT Platforms

Participants: Cedric Adjih, Francois-Xavier Molina, Alexandre Abadie, Koen Zandberg, Emmanuel Baccelli, Chetanveer Gobin, Fernando Molano, Mehdi Debbah.

One necessity for research in the domain of IoT is to establish and improve IoT hardware platforms and testbeds that integrate representative scenarios (such as Smart Energy, Home Automation, etc.) and follow the evolution of technology, including radio technologies and associated experimentation tools. For that, the **TRiBE team** builds upon the evolutions of the **FIT IoT-LAB** federated testbeds towards **SLICES-FR** (through our **5G-mMTC-lab** and **NGC-AIoT** platforms), which the team has contributed to designing and deploying. We plans to further develop FIT IoT-LAB with *Edge AI* and more *heterogeneous*, *up-to-date IoT hardware*, and *radios* to provide a usable and realistic experimentation environment.

On the software side, IoT hardware available so far has made it uneasy for developers to build apps that run across heterogeneous hardware platforms. For instance, Linux does not scale down to small, energy- constrained devices, while microcontroller-based OS alternatives were so far rudimentary and yield a steep learning curve and lengthy development life-cycles because they do not support standard programming and debugging tools. As a result, another necessity for research in this domain is to allow the emergence of it more powerful, unifying IoT software platforms, to bridge this gap. For that, we plan to continue building upon RIOT, a new open source software platform that provides a portable, Linux-like API for heterogeneous IoT hardware. We plan to continue to develop the systems and network stacks aspects of **RIOT**, within the open source developer community currently emerging around RIOT, amd also provide an universal platform that can also be used both (i) in the context of research and/or teaching, as well as (ii) in industrial contexts.

7.3 Open data

Shenzhen dataset

Contributors: Desheng Zhang (zhang@cs.umn.edu), Tian He (tianhe@cs.umn.eud), Fan Zhang (zhangfan@siat.ac.cn)

Description: This 7GB dataset contains five kinds of data: Cellphone CDR Data, Smartcard Data, Taxicab GPS data, Bus GPS data and Truck GPS data of the Chinese City Shenzhen. This dataset is for academic research only. All rights reserved. For privacy concerns, all specific date info was removed and all identifiable IDs have been replaced by serial numbers in each kind of data.

Dataset PID (DOI,...): None.

Project link: Download link.

Publications: Desheng Zhang, Juanjuan Zhao, Fan Zhang, and Tian He. *UrbanCPS: A Cyber-Physical System based on Multi-source Big Infrastructure Data for Heterogeneous Model Integration.* 6th ACM/IEEE International Conference on Cyber-Physical Systems (ICCPS'15), 2015.

Contact: Desheng Zhang (zhang@cs.umn.edu), Tian He (tianhe@cs.umn.eud), Fan Zhang (zhangfan@siat.ac.cn)

Release contributions: Urban Data Release V2 containing 7GB dataset with five kinds of data, as mentioned above.

Sapienza/Probe-Requests dataset

Contributors: Marco V. Barbera, Alessandro Epasto, Alessandro Mei, Sokol Kosta, Vasile C. Perta and Julinda Stefa.

Description: The CRAWDAD Sapienza/probe-requests dataset comprises approximately 11 million Wi-Fi probe requests collected from around 160,000 unique devices in Rome, Italy, between February 5 and May 3, 2013. Data collection took place in Rome, including national political meetings and international events such as the Pope's Angelus at St. Peter's Square, a shopping mall, a train station, and a university campus. This dataset was collected using laptops with tcpdump to capture probe requests. An anonymization procedure was applied to both MAC addresses and SSIDs to ensure privacy. The dataset is available in .pcap format and is intended for research in areas such as social network analysis and human behavior modeling. We highly used this dataset within the ANR MITIK project.

Dataset PID (DOI,...): 10.15783/C76C7Z.

Project link: Download link.

Publications: Marco V. Barbera, Alessandro Epasto, Alessandro Mei, Sokol Kosta, Vasile C. Perta, Julinda Stefa, December 2, 2022, "CRAWDAD sapienza/probe-requests", IEEE Dataport, doi: https://dx.doi.org/10.15783/C76C7Z.

Contact: Marco V. Barbera

8 New results

Activities and related result hereafter described are classified according to the three research axes of the team.

8.1 [Axis 1]: Optimized communication protocols

8.1.1 Modern Random Access: Irregular Repetition Slotted Aloha (IRSA)

Participants: Jia Cao, Cédric Adjih, Paul Mühlethaler *(Inria, EVA)*, Chung Shue Chen *(Nokia Bell Labs)*, Pengwenlong Gu, Saeed Alsabbagh *(Université Paris-Saclay - UVSQ, France & Laboratoire DAVID, France)*, Nadjib Aitsaadi *(UVSQ Paris-Saclay & DAVIDLab, France)*, Amine Adouane *(Benyoucef Benkhedda University, Algeria)*.

Wireless communications play an important part in the systems of the Internet of Things (IoT). Recently, there has been a trend towards long-range communications systems for the IoT, including cellular networks. For many use cases, such as massive machine-type communications (mMTC), performance can be gained by moving away from the classical model of connection establishment and adopting random access methods. Associated with physical layer techniques such as Successive Interference Cancellation (SIC), or Non-Orthogonal Multiple Access (NOMA), the performance of random access can be dramatically improved, giving rise to novel random access protocol designs.

In this line of work, we are studying a modern method of random access for packet networks, named "Irregular Repetition Slotted Aloha (IRSA)", that had been recently proposed: it is based on repeating transmitted packets and on the use of successive interference cancellation at the receiver. In classical idealized settings of slotted random access protocols (where slotted ALOHA achieves $1/e$), it has been shown that IRSA could asymptotically achieve the maximal throughput of 1 packet per slot.

We are also working on the subject in the context of the PEPR-NF, NF-PERSEUS (see for instance [47]).

8.1.2 Optimization of Irregular Repetition Slotted ALOHA with Imperfect SIC in 5G CIoT

Participants: Saeed Alsabbagh *(Université Paris-Saclay - UVSQ, France & Laboratoire DAVID, France)*, Cédric Adjih, Amine Adouane *(Benyoucef Benkhedda University, Algeria)*, Nadjib Aitsaadi *(UVSQ Paris-Saclay & DAVIDLab, France)*.

Irregular Repetition Slotted ALOHA (IRSA) is an effective grant-free random access scheme that is well-suited for managing the sporadic nature of IoT traffic, particularly in dense environments prone to collisions. In this paper, we evaluate the performance of IRSA under realistic conditions involving imperfect successive interference cancellation (SIC) and non-ideal physical layer environments. Specifically, we investigate the impact of various channel conditions and physical layer impairments on IRSA's performance. Previous studies on IRSA often assume ideal physical layer conditions or use simplified models for SIC errors, which fail to fully capture practical implementation complexities. To address this gap, we propose integration of practical factors, such as channel estimation imperfections, into our model of SIC failures using detailed baseband simulations. Based on that, we employ density evolution analysis to evaluate system throughput and optimize the degree distributions to enhance IRSA performance in the presence of imperfect SIC. Our results focusing on 5G CIoT demonstrate that optimizing IRSA parameters, while accounting for SIC errors, can significantly improve system performance, resulting in notable throughput gains.

This article was accepted at ICC 2025.

8.1.3 Automated Header Compression in Constrained Networks

Participants: Soumya Banerjee *(Trasna-Solutions Technologies Ltd., Ireland)*, Dominique Barthel *(Orange Labs, Meylan, France)*, Quentin Lampin *(Orange Labs, Meylan, France)*, Marion Dumay *(Orange Labs, Meylan, France)*, Stéphane Coutant *(Orange Labs, Meylan, France)*, Cédric Adjih, Paul Muhlethaler, Thomas Watteyne.

In low-power wireless networks, every byte sent by an embedded device causes its radio to stay on a little longer, which eats into its limited energy reserve. And because the radio is often the most power-hungry circuit in the device, reducing the number of bytes to be sent and received automatically increases the battery lifetime of the device, resulting in a lower total cost of ownership for the end-user, hence better adoption. Low-power wireless devices tend to generate short data payload, typically in the order of 2-50 B. This means that protocol headers make up a large portion of the bytes inside a wireless frame, 30-70% is not uncommon. Compressing those headers, i.e. removing bytes that can be reconstructed anyways or that are not needed, makes perfect sense. This article serves as a primer on header compression in constrained networks. We start by describing exactly why it is needed, then survey the different standards doing header compression. We indicate how today's approach requires expert input for every deployment, severely hindering the roll-out of such approaches. Instead, we argue that an automated approach based on machine learning and artificial intelligence is the right way to go, and provide blueprints for such approaches.

This article [18] was accepted in the journal IEEE Communications Standards Magazine (Oct 2024).

8.1.4 Demo of Joint Automated Header and Payload Compression in Constrained Networks

Participants: Ichrak Kallala, Thomas Watteyne, Quentin Lampin *(Orange Innovation, Meylan, France)*, Marion Dumay *(Orange Innovation, Meylan, France)*, Stéphane Coutant *(Orange Innovation, Meylan, France)*, Cédric Adjih, Paul Muhlethaler.

Reducing the number of bytes transmitted by a low-power wireless device greatly reduces its power consumption. While header compression is a well-studied topic with solutions such as SCHC that are well-established standards, very little work exists on compressing the payload. This is all the stranger that the payload typically contains more bytes than the headers. This demonstration introduces Dixy, a payload compression technique which can be used alongside SCHC. We implement SCHC and Dixy on the nRF52840, a popular micro-controller. We have them compress packets collected from a real-world deployment by startup company Falco. We show how the resulting joint header and payload compression reduces the number of bytes exchanged between two boards by 74%. The demonstration allows visitors to understand SCHC and Dixy, trigger packets being compressed and transmitted, and observe the number of bytes and the charge consumed with enabling header and/or payload compression.

This work [37] was demonstrated at the IEEE Symposium on Computers and Communications (ISCC) 2024.

8.1.5 Dixy: Transparent Payload Compression for Constrained Networks

Participants: Ichrak Kallala *(Inria, France)*, Trifun Savic *(Wattson Elements/Falco, Paris, France)*, Quentin Lampin *(Orange Lab, Meylan, France)*, Marion Dumay *(Orange Lab, Meylan, France)*, Stéphane Coutant *(Orange Lab, Meylan, France)*, Cédric Adjih *(Inria, France)*, Paul Muhlethaler *(Inria, France)*, Thomas Watteyne *(Inria, France)*.

This paper introduces Dixy, a solution specifically crafted for compressing the application payload of a low-power wireless networking protocol. Dixy is complementary and can be used in parallel to standardized header compression solutions such as 6LoWPAN or SCHC. Dixy operates as a dictionary

compression by identifying a list of patterns and analyzing recently transmitted packets, but without ever having to explicitly share that dictionary with the receiver, as the receiver re-builds the same dictionary from the stream of packets it receives. We show how Dixy outperforms the closest related work by offering a compression factor 29% better by comparing the performance of multiple approaches on a dataset of 1,154,176 packets collected from 614 devices in a real-world commercial deployment. Dixy can be integrated seamlessly with payload security, and made standards-compliant.

The article [36] was presented at IEEE International Conference on Smart Internet of Things (SmartIoT 2024), Nov 2024.

8.2 [Axis 1] Tailored embedded software platforms and Unified low-end IoT technology

8.2.1 Bird song recognition using TinyML models on low-power wireless acoustic sensors

Participants: Zhaolan Huang, Adrien Tousnakhoff, Polina Kozyr, Roman Rehausen, Felix Bießmann, Cédric Adjih, Emmanuel Baccelli.

Monitoring biodiversity at scale is challenging. Detecting and identifying species in fine grained taxonomies requires highly accurate machine learning (ML) methods. Training such models requires large high quality data sets. And deploying these models to low power devices requires novel compression techniques and model architectures. While species classification methods have profited from novel data sets and advances in ML methods, in particular neural networks, deploying these state-of-the-art models to low power devices remains difficult. Here we present a comprehensive empirical comparison of various TinyML neural network architectures and compression techniques for species classification. We focus on the example of bird song detection, and more concretely on a data set curated for studying the corn bunting bird species. We publish the data set along with all the code and experiments of this study. In our experiments we comparatively evaluate predictive performance, memory and time complexity of spectrogram-based methods and of more recent approaches operating directly on the raw audio signal. Our results demonstrate that TinyChirp – our approach – can robustly detect individual bird species with precision over 0.98 and reduce energy consumption compared to state-of-the-art, such that an autonomous recording unit lifetime on a single battery charge is extended from 2 weeks to 8 weeks, almost an entire season.

This work is detailed in [31], published in the IEEE International Symposium on the Internet of Sounds (IS2), in October 2024.

8.2.2 Experimental Embedded Rust Software Platform

Participants: Koen Zandberg, Emmanuel Baccelli, Kaspar Schleiser.

TRiBE has prototyped an experimental re-write of RIOT in Rust, as part of its results of the RIOT-fp project. This experimental embedded software platform is published as open source at Link. As such, RIOT-rs paves the way to a general-purpose OS based on Rust from the ground up for diverse microcontrollers, and for a smooth transition from C to Rust in this domain.

8.3 [Axis 1] Low-footprint cybersecurity mechanisms

8.3.1 Toolkit for Over-the-Air Secure Updates and Performance Evaluation of TinyML Models

Participants: Zhaolan Huang, Koen Zandberg, Emmanuel Baccelli, Kaspar Schleiser
.

Practitioners in the field of TinyML lack so far a comprehensive, "batteries-included" toolkit to streamline continuous integration, continuous deployment and performance assessments of executing diverse machine learning models on various low-power IoT hardware. Addressing this gap, our paper introduces RIOT-ML, a versatile toolkit crafted to assist IoT designers and researchers in these tasks. To this end, we designed RIOT-ML based on an integration of an array of functionalities from a low-power embedded OS, a universal model transpiler and compiler, a toolkit for TinyML performance measurement, and a low-power over-the-air secure update framework—all of which usable on an open-access IoT testbed available to the community. Our open-source implementation of RIOT-ML and the initial experiments we report on showcase its utility in experimentally evaluating TinyML model performance across fleets of low-power IoT boards under test in the field, featuring a wide spectrum of heterogeneous microcontroller architectures and fleet network connectivity configurations. The existence of an open-source toolkit such as RIOT-ML is essential to expedite research combining artificial intelligence and IoT and to foster the full realization of edge computing's potential.

This work is detailed in [21, 55], published in the journal Annals of Telecommunications, in May 2024.

8.3.2 Standardization of Secure Software Updates for Low-power IoT Devices

Participants: Koen Zandberg, Emmanuel Baccelli.

TRiBE co-authors the new IETF standard (work-in-progress) providing low-end IoT devices with secure software updates. The Internet Draft draft-ietf-suit-manifest-31 specifies a Concise Binary Object Representation (CBOR)-based Serialization Format for the Software Updates for Internet of Things (SUIT) Manifest. This specification describes the format of a manifest. A manifest is a bundle of metadata about the firmware for an IoT device, where to find the firmware, the devices to which it applies, and cryptographic information protecting the manifest. Firmware updates and secure boot both tend to use sequences of common operations, so the manifest encodes those sequences of operations, rather than declaring the metadata. The manifest also serves as a building block for secure boot.

This work was published in the IETF Internet Draft draft-ietf-suit-manifest-31, in December 2024.

8.3.3 Tiny Distributed Machine Learning for Microcontroller-Based Interconnected Devices

Participants: Mayank Gulati, Koen Zandberg, Zhaolan Huang, Gerhard Wunder, Cédric Adjih, Emmanuel Baccelli.

More and more, edge devices embark Artificial Neuron Networks. In this context, a trend is to simultaneously decentralize their training as much as possible while shrinking their resource requirements, both for inference and training—tasks that are typically intensive in terms of data, memory, and computation. At the edge's extremity, a specific challenge arises concerning the inclusion of microcontroller-based devices typically deployed in the IoT. So far, no general framework has been provided for that. Such devices not only have extremely challenging resource constraints (weak CPUs, slow network connections, memory budgets measured in kilobytes) but also exhibit high polymorphism, leading to large variability in computational performance among these devices. In this paper, we design and implement TDMiL, a versatile framework for distributed training, and transfer learning. TDMiL interconnects and combines logical components including CoAPerator (a central aggregator) and various tiny embedded software runtimes that are specifically tailored for networks comprising heterogeneous, resource-constrained devices built on diverse types of microcontrollers. We report on experiments conducted with the TDMiL framework, which we use to comparatively evaluate several schemes devised to address computational variability among distributed learning microcontroller-based devices, i.e., stragglers. Additionally, we release the code of our implementation of TDMiL as an open-source project, which is compatible with common commercial off-the-shelf IoT hardware and a well-known open-access IoT testbed.

This work is detailed in [20], published in IEEE Access in November 2024. We also worked on model serialization for transmission over low-power networks. This work, preliminary to our work on TDMiL, was published in [62].

8.4 [Axis 2] Extracting high-end IoT footprints in networking data.

8.4.1 Collecte de traces WiFi publiques: de la protection de la vie privée à l'analyse de trajectoires [Axis 2]

Participants: Fernando Molano Ortiz, Abhishek Kumar Mishra, Fernando Dias de Mello Silva *(Universidade Federal do Rio de Janeiro, Brazil)*, Aline Carneiro Viana, Nadjib Achir, Anne Fladenmuller *(LIP6, Sorbonne Université, Paris, France)*, Luís Henrique Maciel Kosmalski Costa *(Federal University of Rio de Janeiro, Brazil)*.

In today's technological landscape of ubiquitous smartphones and wireless networks, generating digital fingerprints has become a standard method, revealing users' daily habits. In this work, we present a set of tools developed in the context of the ANR MITIK project to collect and analyze WiFi traces. These tools address different challenges, such as guaranteeing an anonymized frames collection to protect users' privacy, managing smartphone MAC address associations, and reconstructing user trajectories. By systematically addressing these challenges, the presented tools facilitate understanding individuals' mobility and establish plausible contacts between various devices.

This work was accepted to be published at CoRes 2024 [39].

8.4.2 Bleach: From WiFi probe-request signatures to MAC association [Axis 2]

Participants: Abhishek Kumar Mishra, Aline Carneiro Viana, Nadjib Achir.

Smartphones or similar WiFi-enabled devices regularly discover nearby access points by broadcasting management frames known as probe-requests. Probe-request frames relay, as information, the MAC addresses of sending devices, which act as the device identifiers. To protect the user's privacy and location, probe-requests use a randomized MAC address generated according to the MAC address randomization protocol. Unfortunately, MAC randomization greatly limits any studies on trajectory inference, flow estimation, crowd counting, etc. To overcome this limitation while respecting users' privacy, we propose `Bleach`, a novel, efficient, and comprehensive approach allowing randomized MAC addresses to device association from probe-requests. `Bleach` models the frame association as a resolution of MAC conflicts in small time intervals. We use time and frame content-based signatures to resolve and associate MACs inside a conflict. We propose a novel MAC association algorithm involving logistic regression using signatures and our introduced time metric. To the best of our knowledge, this is the first work that formulates the probe-request association problem as a generic resolution of conflicts and benchmarks the association with respect to several datasets. Our results show that `Bleach` outperforms the state-of-the-art schemes in terms of accuracy (as high as 99%) and robustness to a wide range of input probe-request datasets. This work was published at Ad Hoc Networks Journal [23] and is related to the ANR MITIK project (2020-2025). It composes the Abhishek's PhD thesis [82] (defended in Oct. 2023), a PhD performed under the supervision of Aline C. Viana and Nadjib Achir.

8.4.3 Do WiFi Probe-Requests Reveal Your Trajectory?

Participants: Abhishek Kumar Mishra, Aline Carneiro Viana, Nadjib Achir.

Human mobility is challenging to infer, reconstruct, or predict precisely and even further through a more privacy-preserving and scalable manner. Domains and applications are: targeted advertising, epidemic prevention, urban, transportation, or touristic planning, to cite a few. Current GPS-based localization methods are considered sparse in space and time, and RSSI-based passive sniffing methods are challenging due to miscellaneous error sources. Recent literature has shown the large and highly

volatile errors in human-location estimation when using observed RSSI from passive sniffing over Wireless packets.

In this work, we propose the first framework that introduces the concept of the user's bounded trajectory. We propose to leverage the signal strength of users' public WiFi probe requests collected from measurements of multiple deployed WiFi sniffers. First, we investigate and characterize errors in RSSI-based radial distance (between the user and each sniffer) estimation. Then, we approximate such radial distances leverage and deduce bounds associated with a user's position. Finally, we infer a user's bounded trajectory using the spatiotemporal bounds of users' locations over time. We guarantee the bounds to enclose a user in space and time, with 95% confidence and a 10% margin of error. Using real-world and large-scale synthetic datasets under heterogeneous contexts and wireless conditions, we infer trajectories with bounds' *width* of less than $10m$ in 70% of cases with users' *inclusiveness* close to 100%.

This work is related to the ANR MITIK project (2020-2025). A journal version of the work is being prepared for submission.

8.4.4 Revealing and exploiting privacy vulnerabilities in users' public wireless packets - Ph.D. thesis

Participants: Abhishek Kumar Mishra, Aline Carneiro Viana, Nadjib Achir.

The increasing proliferation of Wireless Fidelity (WiFi) and Bluetooth Low Energy (BLE) networked devices broadcasting over-the-air unencrypted public packets has raised growing concerns regarding users' privacy. Such public packets consist of management frames, like probe-requests and beacons, necessary for devices to discover available wireless networks and enhance user experience. Revealing the MAC address of a device through public packets allows adversaries to follow the device and do behavioral profiling. Modern devices periodically change/randomize their advertised MAC addresses. Nevertheless, attacks on MAC address randomization have been carried out, demonstrating that randomized addresses from a device can be associated with as little information as the timestamps of their advertised public packets.

In this thesis, we identify key flaws that lead to the MAC association. We assert the flaws by employing our proposed simulation framework to generate large-scale WiFi and BLE passive sniffing traces. We reveal that current device randomization is ineffective and needs revision.

In addition to key flaws identifications, we address the unreliability of existing association frameworks with respective trace collection scenarios to understand the factors contributing to variable association performance. We conduct case studies and introduce benchmarks for evaluating the performance of any association framework. We show the need for a new and effective WiFi MAC association framework, and finally, we develop and benchmark a novel association framework to determine its expected performance with any new input probe-request dataset.

In this thesis, we also identify the limitations of the Received Signal Strength Indicator (RSSI) in accurately inferring user trajectories as a series of timestamped locations due to its high variability. Considering this, we propose a novel concept called "bounded trajectories." Bounded trajectory refers to an area where a particular user is probable to be present across time. We analyze and model the errors associated with radial-distance estimation to derive bounded trajectories that offer high inclusiveness of users' actual trajectory and narrow width throughout its course.

This PhD thesis [82] was performed by Abhishek Kumar Mishra under the supervision of Aline Carneiro Viana and Nadjib Achir and under the ANR MITIK project's funding. Abhishek is currently a Post-Doc fellow at the PRIVATICS team of INRIA Lyon. The MITIK project will finish in February 2025. We publically release in GitLab and Software Heritage, the tools for passive measurement collection developped in the context of the MITIK project: MITIK-SENS, MITIK-LINK, MITIK-MGMT, and MITIK-TRAJ (cf. New Software section).

8.5 [Axis 2] End-users' patterns understanding at the Internet edge.

8.5.1 Predicting Mobility with Small Data and Physical Principles

Participants: Haron Calegari Fanticelli, Antonio Tadeu A. Gomes, Aline Carneiro Viana.

The study of human mobility is fundamental because of its impact on urban planning, the spread of diseases, the well-being of the population, and the mitigation of pollution, among other applications. Among the open challenges in the area, we have as one of the most important the interpretability and generality of the generated models, and the unbalanced volume of available data; several areas have little data available, making it impossible to use existing models.

We intend to face these challenges in a way not addressed before in the literature, which is with the use of mathematical models inspired by natural phenomena—normally modeled as differential equations—combined with established ML techniques to develop prediction models in the area of mobility. We intend with this combination to bring more interpretability to the models and reduce the need for large volumes of data.

This work is focused on the area of **aggregate mobility prediction** because of the data that we have to carry out this work. The available data describe the flow of people between administrative regions of Paris, France, with a sampling frequency of one hour and during fourteen days. More specifically, we intend to model the visitation routine of the people to predict the population density of areas in an instant of time, thus considering mobility and people's routine as a phenomenon to be modeled.

Our work mainly seeks to answer the following problem: **Is it possible, with a good level of assertiveness, to model people's visitation routine through mathematical models combined with machine learning?** Several works available in the literature show that the movements of people are typically characterized by routine behavior: daily cyclical movements (home to work), few places visited in their routine, and displacements that reveal preferred trajectories. The use of mathematical models to add domain knowledge of mobility as a phenomenon in ML techniques is new in the area and to advance this study, bringing more applicability to models, is a valuable knowledge gain for applications in urban planning or epidemiology.

We believe that (in addition to producing a generic interpretable model and requiring less training data to predict the number of people present in each of the study regions at an instant of time) our thesis will open up new opportunities for the development of mobility prediction models that consider other aspects, such as the trajectories that are expected to be taken by individuals or groups of individuals.

Haron has defended his two PhD follow-up examens and the work is still on-going.

8.5.2 POPAyI: *Muscling* Ordinal Patterns for low-complex and usability-aware transportation mode detection

Participants: Aline Carneiro Viana, Isadora Cardoso-Pereira *(UFMG)*, Joao B. Borges *(UFRN)*, Antonio A. F. Loureiro *(UFMG)*, Heitor S Ramos *(UFMG)*.

The comprehension of preferences related to mobility decisions of an urban population opens new perspectives to tackle the consequences of urbanization. Detecting transportation modes' usability in spatiotemporal urban trajectories enriches such mobility comprehension.

With this goal, we introduce POPAyI, a transportation mode detection strategy that bases its design on the Ordinal Pattern (OP) transformation applied to mobility-related time series. POPAyI can quantify time-series dynamics in linear time, *muscling* time series' characteristics that straightforward classification strategies can use. This new strength comes with a low-complex cost, avoiding the need for high computational and methodological complexities in the current Machine Learning (ML) and Deep Learning (DL) literature. POPAyI uses polar geodesic representation and amplitude information in time series, bringing the multivariate capability to the standard uni-dimensional OP transformation.

Our experiments show that POPAyI: (i) perfectly adapts to multi-dimensional mobility time series and individuals' natural non-linear mobility behavior. (ii) presents consistent detection results in any considered number of transportation mode's classes with efficiency in terms of storage and computation complexity, using fewer features than ML approaches and computational resources than DL methods.

Indeed, POPAyI presents classification results equivalent to DL approaches, requiring 10 to 1000 times fewer parameters. For instance, we can increase the F1-score by 3% using 1000 fewer parameters than a lightweight DL approach.

This work was published at the IEEE Internet of Things Journal [19].

8.5.3 Characterizing User Behavior: The Interplay Between Mobility Patterns and Mobile Traffic

Participants: Anne Josiane Kouam, Aline Carneiro Viana, Mariano Beiro.

Mobile devices have become essential tools for capturing human activity, and eXtended Data Records (XDRs) offer rich opportunities for detailed user behavior modeling, crucial for designing personalized digital services. While previous studies have predominantly focused on aggregated mobile traffic and mobility analyses, they often neglect insights at the individual level.

This research develops a novel approach to understanding the dependencies between traffic and mobility behaviors at the user level. By analyzing several features that encompass traffic patterns and mobility aspects of individuals, we enhance the understanding of how these behaviors interact. Unlike existing studies that emphasize aggregated or city-scale analyses, this work directly examines user-specific behaviors, uncovering their potential for fine-grained behavioral modeling. Moving beyond statistical correlations, we focus on dependencies that reveal how mobility directly influences traffic and vice versa.

Our advanced user modeling framework integrates traffic and mobility behaviors over time, capturing fine-grained dependencies while maintaining population heterogeneity through user-specific signatures. Additionally, we introduce a Markov model to infer traffic behavior from mobility and vice versa, prioritizing significant dependencies while addressing privacy concerns. Using a week-long XDR dataset from 1,337,719 users across several provinces in Chile, we validate our approach, demonstrating its robustness and applicability in accurately inferring user behavior and matching mobility and traffic profiles across diverse urban contexts."

This work is under submssion to a ACM journal.

8.5.4 Information-Theoretic tracking of Covid

Participants: Cedric Adjih, Philippe Jacquet.

The outbreak of the pandemic SARS-2 Covid 19 disease has been the major event of these two last years. The subject has given rise to many applications related to information tracking. For example the analysis of urban mobility can be used to predict the evolution of the pandemy. The information theoretic analysis of the covid genome via Joint Complexity can give useful insight about the origin of the virus.

We have edited a special issue in "Entropy" about this subject [22].

8.5.5 Precise Minimax Regret in Logistic Regression

Participants: Michael Drmota, Philippe Jacquet, Wojciech Szpankowski, Changlong Wu.

We study online logistic regression with binary labels and general feature values in which a learner sequentially tries to predict an outcome/ label based on data/ features received in rounds. Our goal is to evaluate precisely the (maximal) minimax regret which we analyze using a unique and novel combination of information-theoretic and analytic combinatorics tools such as the Fourier transform, saddle point method, and the Mellin transform in multi-dimensional settings. To be more precise, the pointwise regret of an online algorithm is defined as the (excess) loss it incurs over a constant comparator (weight vector) that is used for prediction. It depends on the feature values, label sequence, and the learning

algorithm. In the maximal minimax scenario, we seek the best weights for the worst label sequence over all label distributions. For the logistic regression with unbounded weight and when features are uniformly distributed on a d-dimensional sphere or ball we estimate precisely the regret to be in $(d-1)\log T$ larger than $(d/2)\log(T/d)$ for bounded weights. This work has been presented in ISIT 2024 [54].

8.6 [Axis 2] Addressing end-users vulnerability and security concerns in networking data.

8.6.1 Impact of Mobility Patterns on Federated Learning applied to Human Mobility Prediction

Participants: Esper João Paulo *(Universidade Federal de Minas Gerais, Brazil)*, Aline Carneiro Viana, Jussara M. Almeida *(Universidade Federal de Minas Gerais, Brazil)*.

Mobility patterns are inherently linked to human nature (e.g., individual variability, temporal dynamics, behavioral factors, curiosity, social interaction), making mobility prediction a multifaceted and challenging problem that requires sophisticated models and comprehensive data. Machine learning (ML) models excel at predicting the location a person will be at the next time interval, but they often raise privacy concerns. To address these privacy issues while maintaining the benefits of ML models, Federated Learning (FL) offers a distributed framework that enables collaborative training of human mobility prediction models without requiring the sharing of highly sensitive location data. However, in the domain of FL for individual mobility prediction, prior work lacks a thorough understanding of the many factors that may impact the performance of FL-based prediction models. In this work, we provide a comprehensive study of the impact of various aspects related to human behavior, data characteristics, ML algorithmic solutions, and FL architectural structuring. We quantify the impact of such factors on effectiveness (accuracy) and efficiency (execution time, memory, and energy usage) of the prediction, revealing that, ignoring these factors lead to misleading result interpretation, and acknowledging them empowers both effectiveness and efficiency results.

A preliminary version of this work was published as a poster at the NetMob 2023 conference. A full version of this work was then published and presented at the ACM SIGSpatial 2024 conference [29]. Joao Paulo Esper defended his Master thesis in Nov. 2024.

8.6.2 Assessing Shadows in Mobility: Beyond Spatiotemporal Patterns [Axis 2]

Participants: Lucas Gabriel Da Silva Felix, Anne Josiane Kouam Djuigne, Aline Carneiro Viana, Nadjib Achir, Jussara Almeida *(Federal University of Minas Gerais, Brazil)*.

Urban mobility is essential in the 21st century, and the use of mobility-related data has grown to analyze and characterize mobility patterns. This data reveals repetitive behaviors and deviations, making it possible to identify individual users quickly, with just four unique data points identifying 95% of users. The extensive data collection, however, compromises user privacy, prompting two research directions: one focusing on identifying and attacking users and the other, protecting user privacy. Despite privacy techniques like k-anonymity, Differential Privacy (DP), and deep learning-based generative models, attacks exploiting re-identification and unrealistic patterns in synthetic data remain successful, often at the expense of data utility. This work aims to quantify user vulnerability individually, facilitating the design of better privacy methods. Current metrics of uniqueness are computationally expensive, so this study proposes a method using the average distance between neighbors, akin to k-nearest neighbors (k-nn). The preliminary results of the evaluation of general mobility metrics and user embeddings indicate that both approaches can effectively identify private users and those with high vulnerability.

This work was accepted to be published at NetMob 2024 [45]. Another publication is under submission to the SBRC 2025 conference.

8.6.3 Bypass SIMBox frauds in cellular networks

Participants: Anne Josiane Kouam, Aline Carneiro Viana, Alain Tchana.

Due to their complexity and opaqueness, cellular networks have been subject to numerous attacks over the past few decades. These attacks are a real problem to telecom operators and cost them about USD 28.3 Billion annually, as reported by the *Communications Fraud Control Association*. SIMBox fraud, which is one of the most prevalent of these telephone frauds, is the main focus of this work. SIMBox fraud consists of diverting international calls on the VoIP network and terminating them as local calls using an off-the-shelf device, referred to as SIMBox.

In this work, we first survey both the existing literature and the major SIMBox manufacturers to provide comprehensive and analytical knowledge on SIMBox fraud, fraud strategies, fraud evolution, and fraud detection methods. We provide the necessary background on the telephone ecosystem while extensively exploring the SIMBox architecture required to understand fraud strategies. We provide a complete introductory guide for research on SIMBox fraud and stimulate interest for SIMBox fraud detection, which remains little investigated. We also present insights into tomorrow's SIMBox fraud detection challenges. This survey is published in the IEEE Communication and Tutorial Surveys journal [75] and a technical report can be found in [74].

SIMBox fraud involves diverting international cellular voice traffic from regulated routes and rerouting it as local calls in the destination country. It has significantly affected cellular networks worldwide, generating $3.11 Billion of losses annually and threats to national security. Yet, SIMBox fraud is still an open issue being little addressed in the literature and hardly detected by operators due to two main challenges: (c1) the scarcity of ground-truth-enriched datasets and (c2) the difficulty of leveraging detection. In this work, we introduce the FraudZen framework to tackle (c1) by providing mobile communication datasets (i.e., Charging Data Records/CDRs) with real-world fraudulent ground truth. Furthermore, such CDRs are associated with explicit knowledge of the fraudsters' behavior, i.e., a *fraud model*, thus filling the gap for tackling (c2). For this, we first identify real-world fraud capabilities via an extensive review of current in-market simbox appliances. We then introd,uce simbox fraud modeling, grasping fraudsters' intents and enabling the design and forecast of such frauds. Such modeling is embedded in the design of FraudZen opne-source simulator, an environment for the scalable simulation of SIMBbox frauds. It is based on the well-known and broadly used LTE-SIM tool in which we added all the required components to simulate SIMBox fraud. Besides, we inserted various traffic generators and realistic mobility modeling, providing lifelike CDR data and ground-truth for comprehensive fraud detection analysis. We validate FraudZen's ability to simulate efficient fraud models and release related generated CDRs datasets. At last, we leverage FraudZen at the in-depth evaluation of literature ML-based fraud detection while considering several fraud- and detection-related parameters. The obtained insights provide detailed hints to future fraud mitigation design.

The FraudZen simulator (cf. Section 7) is mentioned in the Software section and can be found at Inria GitLab. Related publications were published at IEEE WCNC 2023 [73], at the ACM Conext Student Workshop 2022 [76], at the NetMob 2023 conference, (Book of Abstract) , and at the French Cores 2022 [64] and 2023 [72]. This latter was awarded as the best paper at Cores. An extended version is also under submission.

Recently, an extended version of the paper was accepted at the ACM AsiaCCS 2024 conference [38]. Anne Josiane organised a Hackathon at the université de Yaounde 1, Cameroun, in 2024, which counted on the participation of 20 students.

8.6.4 SigN: Empirical Insights and Practical Solution for SIMBox Fraud Prevention at the Cellular Edge

Participants: Anne Josiane Kouam, Aline Carneiro Viana, Alain Tchana.

Cellular SIMBox fraud bypasses international mobile calls and routes them through the internet as local mobile calls in the destination country, using VoIP GSM gateways equipped with multiple SIM cards, also known as "SIMBox." This fraud causes annual financial losses of up to $3.11 billion, national security threats, and phone conversation privacy breaches. Current approaches to mitigate SIMBoxx fraud present open issues that affect their effectiveness. They lack robustness against the constant refinement of fraudsters' strategies or involve a certain implementation complexity that hinders their widespread deployment in operator networks.

This paper presents Sign, a new mitigation approach based on cellular signaling data analysis. Sign is the first-of-the-literature real-time prevention methodology that is *beyond fraudster-reach and largely deployable*. Sign focuses on the *cellular signaling of user devices during the network attachment*, aiming to block fraudulent SIMBbox devices before they can connect to the network. Through extensive indoor and outdoor experimentation, we empirically show that fraudulent SIMBox devices cause significant latency than legitimate devices during the network attachment. Especially in the authentication phase, fraudulent SIMBox devices' minimum latency is 23× higher than their legitimate counterparts. We analyze such latency overhead, showing it is fundamentally shaped by factors beyond fraudsters' control, i.e., LTE standards for authentication and Internet-based communication related protocols and vagaries. Therefore, we propose a SIMBox fraud prevention approach that adapts the standardized authentication procedure at the cellular edge, at no cost for mobile operators.

This work is under submission to an ACM conference.

8.6.5 Detecting and simulating bypass SIMBox frauds in cellular networks - Ph.D. Thesis

Participants: Anne Josiane Kouam, Aline Carneiro Viana, Alain Tchana.

Cellular networks provide digital communications for more than five billion people around the globe. Besides, their openness to the general public, opaqueness, and complexity have exposed cellular networks to attacks that have tremendously grown over the previous decades. According to the Communication Fraud Control Association's 2021 report, worldwide mobile network operators are experiencing as much as $39.89 billion annually due to illegal activities on their surfaces. Among such illegitimate activities, SIMBox international bypass fraud is one of the most prevalent, having a severe impact manifold.

SIMBox fraud involves diverting international cellular voice traffic from regulated routes and rerouting it as local calls in the destination country from a VoIP-GSM gateway (i.e., SIMBox). Affecting countries worldwide, this problem impairs operators' revenues, network quality, networking research, and national security. Mainly in developing countries, up to 70% of incoming international call traffic is terminated fraudulently. Even worse, SIMBox fraud allows international terrorists to conduct covert activities, masquerading as national subscribers.

In this context, many challenges are added. First, while mobile network datasets (i.e., Charging Data Records or CDRs) are the primary data type leveraged for operators' fraud detection, they are intrinsically private. CDRs hold sensitive information about subscribers' habits, hardening their shareability to the research community and, at the same time, curbing fraud detection investigations. Second, fraudsters' behavior changes over time to adapt to the target solutions, making detection lag behind. In particular, SIMBox fraud increasingly mimics human communication behavior regarding traffic, mobility, and social habits perceptible in CDRs. Third, considering the low related investment, the fraud is quickly profitable. Therefore, the detection time is crucial for effective long-term mitigation.

This thesis tackles international bypass fraud understanding and mitigation while addressing the aforementioned challenges.

- It first deeply surveys both existing literature and the major SIMBox manufacturers to shed light on the SIMBox fraud ecosystem uncovering fraudulent techniques and their constant evolution through time.

- Second, it significantly contributes to unleashing the barrier of real-world CDRs exploitation for research on SIMBox fraud. This includes releasing a scalable simulation environment, i.e., Fraudzen, that generates realistic CDRs, with fraudulent and legitimate users. To this end, Fraudzen

incorporates (i) SIMBox fraud modeling for fraudulent users and (ii) generative modeling capturing real-world communication behaviors for legitimate users. Applying Fraudzen capabilities to the in-depth evaluation of ML-based fraud detection literature reveals that the tackled fraud model variation causes a significant discrepancy in detection performance.

- Third, it investigates the use of cellular signaling data for the real-time detection of bypass fraud through experimental analyzes with real SIMBox appliances.

Through in-depth evaluations, we validate this thesis's contributions to accomplish a pipeline to handle the fraud: *from Fully understanding SIMBox frauds and detection limitations to Long-term fraud mitigation by anticipation and rapid retort.*

This topic was addressed at the Anne Josiane Kouam's PhD thesis [82] under the supervision of Aline Carneiro Viana and Alain Tchana and under INRIA funding. Anne Josiane defended her Ph.D. May 2023 and is currently a Post-Doc fellow at TU-BErlin.

8.7 [Axis 3] Decentralized network mechanisms and architectures

8.7.1 ANSB: An Optimized Network Slicing Scheme for Adaptive Load Balancing in 5G Core Network

Participants: Lam Thanh-Son Nguyen, Nadjib Aitsaadi *(UVSQ Paris-Saclay & DAVIDLab, France)*, Cédric Adjih.

As 5G technology is widely adopted, enterprises seek solutions for automation and rapid service delivery. Network Slicing (NS) leverages 3GPP standards to create multiple, customized network slices on shared infrastructure, serving diverse applications and user groups. This paper focuses on 3GPP 5G Core NS, particularly Release 17, and proposes Adaptive Network Slice Balancing (ANSB) to optimize resource utilization by adjusting User Equipment (UEs) and Protocol Data Unit (PDU) sessions. Extensive experimentation, with 5G OpenAirInterface (OAI) testbed, demonstrates significant improvements in UEs, PDU sessions, and maximize overall data rate consumption.

This article is accepted at the conference ICC 2025.

8.7.2 Theoretical Study of Depth First Search in Random Digraph

Participants: Philippe Jacquet, Svante Janson.

The depth-first search is one of the most used algorithms in computer science. It models in some way the propagation of popularity in a network made of directed arcs and is the foundation of web crawling algorithms. We present the analysis of the depth-first search algorithm in a random digraph model with arbitrary degree distributions. This problem posed by Don Knuth in his next to appear volume of The Art of Computer Programming gives an interesting insight into one of the most elegant and efficient algorithms for graph analysis due to Tarjan.

This work has been presented in AofA 2024 and is published in [34].

8.7.3 Flying 5G Backhaul in Urban Network and Hyperfractal generative models

Participants: Philippe Jacquet, Bernard Mans, Dalia Popescu.

We have investigated mobile networks of Unmanned Aerial Vehicles (UAVs) to extend connectivity and guarantee data rates in the 5G by analyzing possible hovering locations based on limitations such as flight time and coverage. We provide analytic bounds on the requirements in terms of connectivity extension for vehicular networks served by fixed Enhanced Mobile BroadBand (eMBB) infrastructure, where both

vehicular networks and infrastructures are modeled using stochastic and fractal geometry as a model for urban environments.

We prove that assuming n mobile nodes (distributed according to a hyperfractal distribution of dimension d_F) and an average of ρ Next Generation NodeB (gNBs), distributed like a hyperfractal of dimension d_r if $\rho = n^\theta$ with $\theta > d_r/4$ and letting n tending to infinity (to reflect megalopolis cities), then the average fraction of mobile nodes not covered by a gNB tends to zero like $O\left(n^{-\frac{(d_F-2)}{d_r}(2\theta-\frac{d_r}{2})}\right)$. Interestingly, we prove that the average number of drones, needed to connect each mobile node not covered by gNBs is comparable to the number of isolated mobile nodes. We complete the characterization by proving that when $\theta < d_r/4$ the proportion of covered mobile nodes tends to zero. The hyperfractal model can be used to model cities with very few parameters. Furthermore it can be run as a generative models to create an unbounded number of imaginary cities for AI training. This subject relates to the PhD thesis of Geoffrey Deperle and the PEPR MOBIDEC Mob Sci-Dat Factory project.

This work has been published in [84].

8.7.4 Quantum Information theory

Participants: Philippe Jacquet.

The internet beyond current usage naturally extends to quantum network. We are collaborating with the project team PHIQUS on the extrapolation of information theory over quantum networks. The classic quantum entanglement over Bell pairs seems to imply faster than light information transfer. But this is not the case. In our contribution we show that any transfer of information faster than light would imply information transfer backward in time and generate unitarity viilation. This work has been presented in ISIT 2024 in [57].

8.8 [Axis 3] Machine Learning enhanced network protocols and classical network optimization (methods and techniques)

8.8.1 Deep reinforcement learning approach for UAV search path planning in discrete time and space

Participants: Najoua Benalaya *(ENSI, Tunisia, University of Manouba)*, Ichrak Amdouni *(ENSI, Tunisia, University of Manouba)*, Cédric Adjih *(INRIA Saclay, France)*, Anis Laouiti *(Telecom SudParis, France)*, Leila Azouz Saidane *(ENSI, Tunisia, University of Manouba)*.

Path planning for search missions carried out by Unmanned Aerial Vehicles (UAVs) is a challenging problem. This is due to UAV limited energy budget and the importance of time for search operations. The objective of this study is to come up with an approach to minimize the total search time required to locate a specific target. To achieve this, we deployed a deep reinforcement learning (DRL) model based on the Proximal Policy Optimization (PPO) algorithm to solve the combinatorial optimization problem of UAV search path planning within a minimized search time. A smart reward formulation is designed to achieve the learning goal, fulfill the search requirement, and encourage the agent to select search paths that minimize search time. In addition, we employed Optuna hyperparameter optimization framework to systematically select optimal parameters for the PPO model. Most importantly, thanks to the state representation we considered, the model is generalized and adaptable to various search environments. The PPO model succeeds to compute an accurate search path to be followed by the UAV searcher. Results of the model are compared with results previously obtained with a linear program. We found that the PPO achieves almost the same expected search time, which proves the great relevance of the reward design and the hyperparameters selection we made.

This work [24] was presented at the 20th International Wireless Communications and Mobile Computing (IWCMC), May 2024.

8.8.2 NetDiff: Deep Graph Denoising Diffusion for Ad Hoc Network Topology Generation

Participants: Félix Marcoccia *(INRIA Paris, Paris; Thales SIX, Gennevilliers, France; Sorbonne Université, Paris, France)*, Cédric Adjih, Paul Mühlethaler *(INRIA Paris, AIO)*.

This paper introduces NetDiff, an expressive graph denoising diffusion probabilistic architecture that generates high-performance link topologies for wireless ad hoc networks. Such networks, when equipped with directional antennas, can achieve unmatched throughput and scalability if the communication links are designed to provide good geometric properties. This topology refinement notably involves reducing interference between these links while respecting diverse physical constraints. The crafting of such a link assignment algorithm remains a real problem. Deep graph generation offers several advantages over traditional approaches: it eliminates the need for nodes to perform decentralized, dynamic computations of viable communication routes and avoids relying on heavy combinatorial methods to determine an optimal link topology. Given that graph neural networks tend to struggle with global, structural properties, we augment the popular graph transformer with novel cross-attentive modulation tokens in order to enhance global control over the predicted topology. We also incorporate simple node and edge features, as well as additional loss terms, to facilitate compliance with the physical constraints of the network topology. A network evolution algorithm based on partial diffusion is also proposed to maintain the network topology over time when the nodes move. Our results show that the generated topologies are realistic, require only minor correction steps to be operational, and establish NetDiff as a viable solution to maximize the benefits offered by directional antennas.

A variant of this preprint [81] had been accepted to the AAAI 2025 workshop on Artificial Intelligence for Wireless Communications and Networking (AI4WCN).

8.8.3 AutoMHS-GPT: Automated Model and Hyperparameter Selection with Generative Pre-Trained Model

Participants: Lucas Airam Castro de Souza, Matteo Sammarco *(Federal University of Rio de Janeiro, Brazil)*, Nadjib Achir, Miguel Elias Mitre Campista *(Federal University of Rio de Janeiro, Brazil)*, Luís Henrique Maciel Kosmalski Costa *(Federal University of Rio de Janeiro, Brazil)*.

Automated Machine Learning emerges as a solution to reduce the instantiation time of systems that rely on Artificial Intelligence (AI) by accelerating the search process for models and hyperparameters. These techniques, however, still require high execution time. In critical applications, such as intrusion detection in vehicular networks, delays in applying countermeasures can provoke accidents. Therefore, it is essential to guarantee accurate models in the shortest possible time to detect threats effectively. This work proposes AutoMHS-GPT, a system that uses generative artificial intelligence to reduce the time it takes to define hyperparameters and models when implementing machine learning to detect threats in vehicular networks. Based on a description of the problem, the generative model returns a text containing the appropriate model with its hyperparameters for training. Results show that AutoMSH-GPT produces models with higher threat classification performance than automated machine learning approaches AutoKeras and Auto-Sklearn, increasing in the best case the recall by 9%. Furthermore, the current proposal reduces the model search and training process, carrying out the task in around 30 minutes, while the other evaluated frameworks require two to three days.

This work was accepted to be published at IEEE International Conference on Cloud Networking – CloudNet 2024 [27] and Brazilian symposium SBRC 2024 [26].

8.8.4 Improving Global Awareness of Linkset Predictions using Cross-Attentive Modulation Tokens

Participants: Félix Marcoccia *(INRIA Paris, Paris; Thales SIX, Gennevilliers, France; Sorbonne Université, Paris, France)*, Cédric Adjih, Paul Mühlethaler *(INRIA Paris, AIO)*.

This work introduces Cross-Attentive Modulation (CAM) tokens, which are tokens whose initial value is learned, gather information through cross-attention, and modulate the nodes and edges accordingly. These tokens are meant to improve the global awareness of link predictions models which, based on graph neural networks, can struggle to capture graph-level features. This lack of ability to feature high level representations is particularly limiting when predicting multiple or entire sets of links. We implement CAM tokens in a simple attention-based link prediction model and in a graph transformer, which we also use in a denoising diffusion framework. A brief introduction to our toy datasets will then be followed by benchmarks which prove that CAM token improve the performance of the model they supplement and outperform a baseline with diverse statistical graph attributes.

This work is available in the preprint [80].

8.9 [Axis 3] Edge network offloading (methods and techniques)

8.9.1 Can Vehicular Cloud Replace Edge Computing?

Participants: Rosario Patanè *(University Paris-Saclay, France)*, Andrea Araldo *(Télécom SudParis)*, Nadjib Achir, Lila Boukhatem *(University Paris-Saclay, France)*.

Edge computing (EC) consists of deploying computation resources close to the users, thus enabling low-latency applications, such as augmented reality and online gaming. However, large-scale deployment of edge nodes can be highly impractical and expensive. Besides EC, there is a rising concept known as Vehicular Cloud Computing (VCC). VCC is a computing paradigm that amplifies the capabilities of vehicles by exploiting part of their computational resources, enabling them to participate in services similar to those provided by the EC. The advantage of VCC is that it can opportunistically exploit part of the computation resources already present on vehicles, thus relieving a network operator from the deployment and maintenance cost of EC nodes. However, it is still unknown under which circumstances VCC can enable low-latency applications without EC. In this work, we show that VCC has the potential to effectively supplant EC in urban areas, especially given the higher density of vehicles in such environments. The goal of this paper is to analyze, via simulation, the key parameters determining the conditions under which this substitution of EC by VCC is feasible. In addition, we provide a high level cost analysis to show that VCC is much less costly for a network operator than adopting EC.

This work was accepted to be published at IEEE WCNC'24 [40].

8.9.2 On the Edge of the Deployment

Participants: Pedro Cruz, Aline Carneiro Viana, Nadjib Achir.

Multi-Access Edge Computing (MEC) attracts much attention from the scientific community due to its scientific, technical, and commercial implications. Still, MEC remains unfinished. In their majority, the existing MEC implementations are incomplete, which hardens or invalidates their practical deployment. As an effort to the future solutions aiming to fill this gap, it is essential to study and understand a series of experimental implementations and deployments. In this context, this work first brings a discussion on existing MEC implementations regarding the applications they target and their vision (i.e., whether they are more network-related or more distributed systems). Second, we list literature on MEC implementations according to their strategies and their consequences for the overall implementation project. We then discuss the deployment effort for each implementation. We also compare the tools developers used

to make their MEC systems a reality. Finally, we discuss the issues that MEC implementations are yet to address. By bringing a better comprehension of MEC implementations, we hope this work will help developers develop their own or use MEC implementations.

This work was firstly published at the ACM Computing Surveys Journal [68]. It is an on-going work with the analysis of implications that a wrong mobility management imposes to the MEC infrastructure in relation with the PEPR NF NAI and the funding of a Post-Doc.

8.9.3 Data offloading decision via mobile crowdsensing

Participants: Emanuel Lima *(U. of Porto)*, Aline Carneiro Viana, Ana Aguiar *(U. of Porto)*, Paulo Carvalho *(Univ. Do Minho)*.

Several studies on the analysis of human mobility patterns have been carried out focusing on the identification and characterization of important locations in users' life in general. We extended these works by studying human mobility from the perspective of mobile data offloading. In our first study, We define Offloading Regions (ORs) as areas where a commuter's mobility would enable offloading, and propose an unsupervised learning method to extract ORs from mobility traces.

Next, we leverage human mobility to inform offloading tasks, taking a data based approach leveraging granular mobility datasets from two cities: Porto and Beijing. We evaluate the offloading opportunities (ORs) provided to users while they are travelling in terms of availability, time window to offload, and offloading delay. Results show that in 50% of the trips, users spend more than 48% of the travel time inside ORs extracted according to the proposed method. Moreover, results also show that (i) attending to users mobility, ten seconds is the minimum offloading time window that can be considered; (ii) offloading predictive methods can have variable performance according to the period of the day; and (iii) per-user opportunistic decision models can determine offloading system design and performance. This work was published at ACM CHANTS 2018 (jointly with ACM MobiCom) [79]. Next we extended the above work as following.

We then assess the mobility predictability in an offloading scenario using theoretical and algorithmic evaluation of several mobility predictors. The results show that mobility predictability for offloading purposes is far more challenging than mobility between PoIs. Here, machine learning (ML) predictors outperform common Markov Chain (MC) predictors used in the literature by at least 15%, revealing the importance of context information in an offloading scenario. The conclusions and findings on offloading mobility properties are likely to generalise for varied urban scenarios given the high degree of similarity between the results obtained for the two different and independently collected mobility datasets. This extended work was published at the IEEE Transactions on Network and Service Management [78].

Further, we examine the effects of employing diverse context information during AP selection in the offloading process. Findings indicate that mobility information notably reduces connection attempts and significantly prolongs offloading connection duration, particularly during vehicle commutes, but has minimal impact on offloading efficiency. On the other hand, utilizing accurate network data enables offloading systems to approach the upper limit for offloading efficiency, even with shorter offloading time windows. Finally, a novel offloading approach leveraging users mobility and soft-handovers between APs is investigated revealing significant efficiency gains and reduced connection attempts across various commute scenarios. This work is under submission to a IEEE journal

The work and the collaboration with the PhD Emmanuel Lima is still on-going, a collaboration started when he spent 4 months in 2018 as an intern in our previous team, and his advisors.

8.9.4 DynSplit: A Dynamic Split Learning Scheme for 5G-Enpowered Metaverse

Participants: Yunmeng Shu, Pengwenlong Gu, Cédric Adjih, Chung Shue Chen, Ahmed Serhrouchni.

The Metaverse is a virtual world based on numerous technologies, which enables users to interact socially in a persistent online 3-D virtual environment. To generate high-level imaginary environments,

extremely low latency data transmission and learning-based sensor data analysis are required. With the development of 5G techniques, processing and learning methods, both the transmission delay and high-quality scene generation have been significantly improved in meta-applications. However, many Metaverse devices are battery-powered, and local processes and learning are still too costly. To address this issue, in this paper, by taking full architectural advantage of 5G networks, we propose a novel dynamic split learning scheme for enabled Metaverse systems. In our proposed scheme, each neural network is split into two segments, and the upper segment is stored at the base station (BS) side. Thus, between two segments, multiple pathways are featured, each with distinct compression ratios, accompanied by a gating mechanism that intelligently guides the selection of paths for each input data. This design excels in adapting to diverse Metaverse applications and network conditions, enhancing both the learning and computing phases of split models. Simulation results underscore the efficacy of our proposed scheme, revealing that it does not impede the convergence of split learning models. Furthermore, the scheme demonstrates notable performance gains in terms of communication overhead, prediction accuracy, and adaptability to resource constraints.

This article [46] was presented at MetaCom 2024

8.9.5 Edge AI

Participants: Cédric Adjih, Nadjib Achir, Amira Dhaouadi, Emmanuel Baccelli, Yijie Luo, Fernando Molano, Mehdi Debbah, Yunmeng Shu, Pengwenlong Gu.

This year, work continued on the topic of EdgeAI; in particular, we continued to work on the novel technique for embedded IoT systems that uses support from edge or cloud servers, and we proposed a split-computing model. We also experimented with developing models on Nvidia Jetson Nano/Xavier/Orin embedded AI boards, for specific applications, and continued develop an testbed system.

8.10 [Axis 3] Security of the edge/core compound including IoT deployments (technologies)

8.10.1 Delay analysis of the BFT blockchain data dissemination: case of Narwhal protocol

Participants: Khouloud Hwerbi *(ENSI, Tunisia, University of Manouba)*, Ichrak Amdouni *(ENSI, Tunisia, University of Manouba)*, Cédric Adjih, Philippe Jacquet, Leila Azouz Saidane *(ENSI, Tunisia, University of Manouba)*, Anis Laouiti *(Telecom SudParis, France)*.

This article investigates data dissemination delays in a Directed Acyclic Graph (DAG)-based Byzantine Fault Tolerant (BFT) blockchain. We focus particularly on the Narwhal protocol, a mempool-based approach for efficiently disseminating transactions and constructing a DAG. Narwhal is designed to work alongside a BFT consensus protocol like Tusk. Tusk then orders the transaction metadata based on the DAG information. Through an in-depth analysis of the protocol messages, we establish a mathematical model for message propagation delays. We start by considering a specific probability distribution for data network propagation delays: Gaussian Distribution. Then, we consider a general propagation delay distribution. Also, we assume large networks and apply some approximations, i.e., the Central Limit Theorem (CLT). Finally, we develop the Narwhal protocol and demonstrate that the simulated delays are compatible with the theoretical ones.

This work [33] was presented at the conference IEEE International Conference on Wireless and Mobile Computing, Networking And Communications, WiMob 2024.

8.10.2 Delay analysis of a mempool-based blockchain protocol under asymptotic hypothesis

Participants: Khouloud Hwerbi *(ENSI, Tunisia, University of Manouba)*, Ichrak Amdouni *(ENSI, Tunisia, University of Manouba)*, Cédric Adjih, Philippe Jacquet, Leila Azouz Saidane *(ENSI, Tunisia, University of Manouba)*, Anis Laouiti *(Telecom SudParis, France)*.

Delays in blockchain networks are mainly related to consensus protocols. Among these protocols, we focus on a specific family of protocols, where the mempool's role in the consensus mechanism is explicitly examined. A mempool is a temporary storage area for transactions waiting to be included in a block. This study investigates the round duration of two mempoolbased protocols: one requiring a single quorum of messages and another demanding two. We perform the delay analysis with two approaches. First, we elaborate on a Markov chain to determine the distribution of the round durations. Second, we establish an analytical model of message delays while assuming an exponential distribution of message propagation delays. Finally, asymptotic analysis is conducted to estimate the time of quorum formation. We end the paper by comparing the simulation results with the theoretical ones. Results show that both results are very close. This research offers valuable insights into the performance characteristics of mempool-based consensus protocols, aiding in the design and optimization of blockchain systems.

The article [32] was presented at the International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks, PEMWN 2024

8.10.3 Secured Contact Tracing for Epidemic Transmission Prevention in Smart Farming Applications

Participants: Rihab Boussada *(National School of Computer Sciences (ENSI) University of Manouba, Tunisia)*, Leila Nasraoui *(National School of Computer Sciences (ENSI) University of Manouba, Tunisia & COSIM Research Lab. Higher School of Communications (SUP'COM), University of Carthage, Tunisia)*, Cédric Adjih, Leila Azouz Saidane *(National School of Computer Sciences (ENSI) University of Manouba, Tunisia)*.

Livestock farming in agriculture has recently witnessed the surge of integrating various information and communication technologies for digital farming that improve the efficiency of resource use and increase the added value of agricul-tural products. In this context, this paper proposes a pioneering secured solution for cattle health monitoring. In particular, we focus on secured tracing of animals that have recently been in the vicinity of an infested one. We propose a new message structure that enables real-time detection based on the signal strength. Secured message exchange is ensured through Elliptic curve cryptography. Further, to avoid potential falsification of epidemic history, we develop a mechanism capable of detecting malicious messages wrongly claiming infection. Performance study shows that the proposed model satisfies all privacy requirements in the context of contact-tracing applications.

This work [66] was presented at PEMWN 2024.

8.10.4 Blockchain adapted to IoT

Participants: Philippe Jacquet.

Blockchain applications continue to grow in popularity, but their energy costs are clearly becoming unsustainable. In most cases, the primary cost comes from the amount of energy required for proof-of-work (PoW). Here we study the application of blockchains to the IoT, where many devices are underpowered and would not support the energy cost of proof of work. PoW was originally intended for two main uses: block moderation and protecting the blockchain from tampering. The first use is by far the most energy eater. It has already been proposed to replace the expensive moderation by PoW with the energy-efficient green mining. Free from the block moderation burden, the PoW can be made much lighter and adapted to the power diversity of the miners. We propose a fractal difficulty PoW. Used alone we show that the

fractal PoW does not really reduce the energy cost for the low powered nodes. However when associated with green election which guarantees a finite period of fairness indifferent to PoW after each block mined, we show that the fractal PoW indeed reduces the energy for the low powered devices while keeping the same protection against blockchain tempering. In passing we show that a certain monotonicity condition is not met by PoW.

This work was presented in PEMWN 2023 [71] and the work is still on-going.

9 Bilateral contracts and grants with industry

9.1 Bilateral grants with industry

Thalès - CIFRE Thesis

Participants: Cedric Adjih, Paul Muhlethaler, Felix Marcoccia.

Felix Marcoccia is a CIFRE student at Thalès, co-advised at Inria by P. Mühlethaler and C.Adjih, on the subject of: "Study of MANET Solutions for a Radio Communication System Based on Artificial Intelligence Algorithms"

Qualcomm - Donation

Participants: Emmanuel Baccelli, Philippe Jacquet.

We have finalized a donation process from Qualcomm industry, starting year 2024 and supporting the research on wireless IoT and routing, in particular the experimentation of local wireless bubble based on Bluetooth.

Fujitsu / RunMyProcess - Donation

Participants: Emmanuel Baccelli.

100 kEUR. We have received this donation to support us in developing and maintaining RIOT.

PADAM Mobility - CIFRE Thesis

Participants: Aline Carneiro Viana, Mohamed Ourahou.

Mohamed Ourahou is a CIFRE PhD student at PADAM Mobility (Siemens Mobility Group - Paris), co-advised at Inria by A. Carneiro Viana, at Telecom SudParis by A. Araldo, and at PADAM Mobility by L. Zigrand, on the subject of: "Geostatistical and Machine Learning Methods for Sustainable Deployment of Mobility on Demand".

SAFRAN- CIFRE Thesis

Participants: Cedric Adjih, Paul Muhlethaler, Corentin Gautier.

Corentin Gautier is a CIFRE PhD student at SAFRAN Electronics & Defense, co-advised at Inria by P. Mühlethaler and C. Adjih, on the subject of: "FANET for Vehicles Swarms".

10 Partnerships and cooperations

10.1 International initiatives

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

MAGICO Inria Associate team

Participants: Cedric Adjih.

Title: Machine-Learning Enabled Next-Generation IoT Communications

Duration: 2022 ->

Coordinator: Sanjeev Sharma (sanjeev.ece@itbhu.ac.in)

Partners: Inria and Indian Institute of Technology, Varanasi ITT (BHU) (Inde)

Inria contact: Cédric Adjih

Summary: The proposed Associated Team is focusing on modern communications for the Internet of Things (IoT), for 5G and beyond. Traditionally the wireless network systems have been designed in "layers" (e.g. OSI Layers). This is especially true for cellular communications, the main focus of this proposition. Designing next-generation communications for IoT requires revisiting this separation of layers, for some important use-cases, such as Industrial IoT and/or massive Machine Type Communications, and this will be the key of this project. We rely on the expertise of both teams. In addition, Machine Learning techniques are methods of prime interest to improve the performance of these communication methods. Specifically, we will devise an architecture for IoT communications that is based on a mix of the principles of the methods "Irregular Repetition Slotted ALOHA" (IRSA), of the methods of type "Non-Orthogonal Multiple Access" (NOMA), in particular, Sparse-Code Multiple Access (SCMA) - their principles are similar, and each partner of the Associated Team has expertise in one, or several of these. We will provide novel, efficient, variants of these protocols. Another important contribution of the project will be the addition of "sensing" of the active devices, which is extremely important in IoT scenarios; it is well-known in non-cellular networks, but it is much less explored in cellular networks, as it was unnecessary for non-IoT communications. We intend to develop machine learning-based, compressive-sensing-based, and group-testing-based methods for sensing in SA. Furthermore, the pattern of transmission of the devices (the codewords of SCMA) can be designed and assigned to the users dynamically using deep-learning-based methods. Finally, the proposed algorithms and methods will be implemented and demonstrated in an IoT testbed.

10.1.2 STIC/MATH/CLIMAT AmSud projects

STIC AmSud LINT

Participants: Nadjib Achir, Aline Carneiro Viana, Anne Josiane Koaum.

Title: Machine-Learning Enabled Next-Generation IoT Communications

Program: STIC-AmSud

Duration: January 1, 2023 – December 31, 2024

Coordinator: Nadjib Achir

Partners:

- Universidade Federal do Rio de Janeiro, Universidade Federal de Minas Gerais, Universidade Federal de Goiás (Brazil)
- Universidad del Desarrollo (Chile)
- University Sorbonne Paris Nord, Inria **From TRiBE**: Nadjib Achir and Aline Carneiro Viana (France)

Inria contact: Nadjib Achir

Web link: STIC-AmSud LINT web site

Summary: LINT focuses on developing privacy-preserving mobility models using federated learning, adaptive resource management strategies for latency-sensitive Tactile Internet applications, and practical experimentation within MEC infrastructure. These efforts aim to enhance user privacy and optimize resource allocation.

10.1.3 Participation in other International Programs

PHC ANGEL 2024-

Participants: Cedric Adjih.

Title: *"Agriculture Numérique et 'diGital twin' face aux changements climatiques pour une sÉcurité aLimentaire"* (PHC-Maghreb 2024) [link]

Coordinator: Telecom SudParis (France), ENSI/U. of Manouba (Tunisia), ENSIAS (Morocco)

Partners: Laboratoire CRISTAL, ENSI Tunisia, Telecom SudParis, IPP, France Inria Saclay, France. **From TRiBE**: Cedirc Adjih.

Description: The project aims to enhance agricultural resilience and sustainability against climate change and food security challenges through advanced technologies like Digital Twin (DT), AI, IoT, UAVs, and Blockchain.rance)

10.2 International research visitors

10.2.1 Visits of international scientists

Other international visits to the team

Alejandro Lage Castellanos

Status (researcher, PhD, post-Doc, intern (master/eng))

Institution of origin:

Country: Cuba

Dates: 21st-27th January 2024

Context of the visit: Cellular datasets and mobility knowledge extraction to improve services, applications, land use or mobility behavior understanding.

Mobility program/type of mobility: Research stay.

10.3 European initiatives

10.3.1 Other european programs/initiatives

TinyPART (2021–2024):

Participants: Emmanuel Baccelli.

Title: Tiny, PrivAte, pRoven and isolaTed (ANR/BMBF French German Cybersecurity Program) [link]

Coordinator: Orange.

Partners: FU Berlin, Lille University, and PHYSEC GmbH. **From TRiBE**: Emmanuel Baccelli

Description: TinyPART develops Software-Defined IoT building blocks for low-power devices, emphasizing privacy-by-design and cybersecurity. It enables isolating untrusted IoT logic, integrating privacy-oriented preprocessing like differential privacy and lightweight cryptography. Built on RIOT OS and PIP, TinyPART explores tradeoffs between isolation, security, memory footprint, and developer usability.

Team contribution: novel designs for tiny software containers and experimental platforms for TinyML. Open-source implementations of these designs were upstreamed to RIOT.

10.4 National initiatives

IoT-LAB (now part of SLICES-FR):

Participants: Cedric Adjih, Fernando Molano, Emmanuel Baccelli.

Partners: Sorbonne Université, Inria (Lille, Sophia-Antipolis, Grenoble), INSA, Institut Telecom Paris, Institut Télécom Evry, LSIIT Strasbourg.

Abstract: FIT (Future Internet of Things) had developed an experimental facility, a federated and competitive infrastructure with international visibility and a broad panel of customers. It provides this facility with a set of complementary components that enable experimentation on innovative services for academic and industrial users. The project gave french internet stakeholders a means to experiment on mobile wireless communications at the network and application layers thereby accelerating the design of advanced networking technologies for the future internet.

SLICES-FR is a larger-scale ongoing effort to provide such platforms, a follow-up and much more.

One component of the existing platforms is the sets of IoT-LAB testbeds (see the IoT-LAB web site). These were motivated by the observation that the world is moving towards an “Internet of Things”, in which most communication over networks will be between objects rather than people.

Project 5G-mMTC:

Participants: Cedric Adjih, Alexandre Abadie *(Inria, SED)*, Nadjib Achir, Fernando Molano, Emmanuel Baccelli.

Funding instrument: AAP - Plan de relance « Souveraineté dans les réseaux de télécommunications afin d’accélérer les applications de la 5G » (France Relance)

Project acronym: 5G-mMTC

Duration: 2021–2024

Partners: Amarisoft, EDF R&D, Fédération francaise de cyclisme, Inria Saclay, Institut Mines Telecom, IS2T, Sequans communications, Sparkling Tech, Université de Versailles (UVSQ Paris-Saclay), Webdyn

Website: 5g-mMTC web site

Abstract: The 5G-mMTC project aims to provide software and hardware tools for the rapid implementation of a 5G solutions for the IoT. Two use cases will be implemented directly within the framework of this project: one developed in conjunction with the French Cycling Federation (FFC), which will enable real-time analysis of athletes' data and their performances; the other will be worked on jointly with EDF, to enable real-time management of the entire fleet of existing heterogeneous sensors

Inria Challenge on Federated Learning FedMalin:

Participants: Cedric Adjih, Aline Carneiro Viana, Nadjib Achir.

Partners: Inria Teams (ARGO, COATI, COMET, EPIONE, MAGNET, MARACAS, NEO, SPIRALS, TRIBE, WIDE).

Abstract: FedMalin is a research project that spans 10 Inria research teams and aims to push FL research and concrete use-cases through a multidisciplinary consortium involving expertise in ML, distributed systems, privacy and security, networks, and medicine. We propose to address a number of challenges that arise when FL is deployed over the Internet, including privacy & fairness, energy consumption, personalization, and location/time dependencies. FedMalin will also contribute to the development of open-source tools for FL experimentation and real-world deployments, and use them for concrete applications in medicine and crowdsensing. The FedMalin Inria Challenge is supported by Groupe La Poste, sponsor of the Inria Foundation.

10.4.1 ANR

MITIK

Participants: Aline Carneiro Viana, Nadjib Achir, Abhishek Mishra, Catuscia Palamidessi, Fernando Molano.

Funding instrument/scientific committee: PRC/CE25

Project acronym: MITIK

Project title: Mobility and contact traces from non-intrusive passive measurements

Duration: 2020–2025

Coordinator: Aline Carneiro Viana

Other partners: COMETE/Inria, Universite de la Rochelle, Sorbonne Universite (UPMC).

Budget: 644K€, TRiBE (289K€)

Web link: ANR MITIK website

Abstract: The MITIK project is a 42-month ANR project that will start in February 2020. Mitik's primary objective is the design of an entirely new methodology to help the community obtain real wireless contact traces that are non-intrusive, representative, and independent of third parties. The secondary outcome of the project is be the public release of (1) the measurement tool designed for the easy contact gathering task; (2) contact traces which are clean, processed, and privacy-preserving, i.e., protecting both the anonymity and the location privacy of the users; and (3) their spatiotemporal statistical analysis. We expect that Miti's outcomes will support non-biased research on the modeling as well as on the leveraging of wireless contact patterns.

PEPR NF FITNESS

Participants: Aline Carneiro Viana, Cedric Adjih, Nadjib Achir, Emmanuel Baccelli, Amira Dhaouadi. .

Funding instrument/scientific committee: PEPR Networks of the Future - ANR

Project acronym: NF FITNESS

Project title: From IoT breakthroughs to Network Enhanced ServiceS

Duration: 2023–2030

Coordinator: Eric Mercier (CEA)

Inria co-pilot: Nadjib Achir (TRiBE, INRIA)

Other partners: IMT, CNRS, INRIA (AGORA, AIO, FUN, TRiBE)

Budget: 4.9M€, INRIA (900K€), TRiBE (290K€)

Web link: NF FITNESS website

Abstract: The FITNESS project aims to provide elementary blocks and define the conditions for their integration into vertical applications with a guarantee of coexistence for IoT. Three areas are addressed: Massive IoT (low consumption and low cost), Industry 4.0 (Mission Critical connectivity), and Vehicular and Connected Transport (towards Autonomous Mobility). The key elements to consider are the evolution towards standard protocols and the general coexistence of new networks post-5G. Indeed, factories and manufacturing centers are attentive and eager to evolve toward digitization and wireless connectivity. However, robustness and the ability to perform critical missions will be crucial. In parallel, new services include digital twins and connected and autonomous mobility. Therefore, it is essential to ensure connectivity and access to safe, permanent, and guaranteed resources. The NF-FITNESS will address the challenges raised by these three main domains. The research will include PHY, NETWORK, and APPLICATION layers to generate outcomes tailored to specific verticals. The collaboration aims to:

- Enhance the performance of foundational components, serving as a foundational application for Massive IoT, focusing on seamless integration.
- Investigate the unique requirements of Mission Critical applications, prioritizing robustness as the most critical factor.
- Foster the development of resource sharing and interoperability, emphasizing the challenges associated with data processing.

PEPR NF NAI

Participants: Aline Carneiro Viana, Nadjib Achir.

Funding instrument/scientific committee: PEPR Networks of the Future - ANR

Project acronym: NF NAI

Project title: Architectures and Infrastructures de Réseaux et Convergence réseaux, cloud and capteurs

Duration: 2023–2030

Coordinator: Gérard Memmi (IMT)

Other partners: IMT, CNRS, EURECOM, INP Toulouse, CentraleSupélec, INRIA (AGORA, DIANA, RESIST, TRIBE)

Budget: 5M€, INRIA (490K€), TRiBE (200K€)

Web link: NF NAI website

Abstract: Beyond traditional objectives (throughput, execution speed, latency, object connection density, etc.), the NF-NAI project must allow the effective integration of a multitude of new technologies, such as those of the physical layer (reconfigurable intelligent surfaces) or the transition to 3D (NTN – Non-Terrestrial Networks) and architectural principles (such as slicing and end-to-end dynamic orchestration). It must facilitate the emergence of new applications and services, thanks to transparency in terms of performance, robustness, and security with respect to the use cases. The project will also have to propose and create interfaces with converged network-cloud-sensing systems to offer a high degree of transparency to developers of applications ranging from the edge to the cloud, from mini-connected objects to large data centers through Multi-access edge computing (MEC).

PEPR NF PERSEUS

Participants: Cedric Adjih, Paul Mühlethaler.

Funding instrument/scientific committee: PEPR Networks of the Future - ANR

Project acronym: NF PERSEUS

Project title: Power-Efficient Radio interface for Sub-7GHz distributEd massive MIMO infrastructUreS

Duration: 2023–2030

Coordinator: Rafik Zayani (CEA-Leti)

Other partners: IMT, CNRS, INRIA (MARACAS, TRiBE, EVA)

Budget: 5M€, INRIA (300K€), TRiBE (70K€)

Web link: NF PERSEUS website

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

PEPR NF FPNG

Participants: Cedric Adjih, Fernando Molano.

Funding instrument/scientific committee: PEPR Networks of the Future - ANR

Project acronym: NF FPNG

Project title: French Network of Test Platforms for the Next Generation of Mobile Communications

Duration: 2023–2030

Coordinator: Philippe Besnier (CNRS)

Other partners: IMT, EURECOM, CNRS, Sorbonne Université, INRIA (MARACAS, TRiBE, EVA)

Budget: 4.5M€, INRIA (1.4M€), TRiBE (157K€)

Web link: NF FPNG website

Abstract: The objective of the FPNG project is to build a research infrastructure on a national scale to test new hardware components and evaluate the new paradigms of the next generation of telecommunications networks. These research infrastructures target both core technology components and end-to-end network testing. This platform program aims to address all relevant technologies, ranging from elementary electronic components to large-scale networking experiments, to address all the specific challenges of the PEPR Networks of the Future. The objective is to grant the researchers of this PEPR free access to existing infrastructures and to invest in new strategic and advanced infrastructures when they still need to be created to respond to the new challenges.

PEPR MOBIDEC Mob Sci-Dat Factory

Participants: Aline Carneiro Viana, Nadjib Achir, Philippe Jacquet, Lucas de Souza Felix, Geoffrey Deperle, Anne Josiane Kouam.

Funding instrument/scientific committee: PEPR MOBIDEC (Data technology for Mobility in the teriitories) - ANR

Project acronym: Mob Sci-Dat Factory

Project title: Sharing of tools for processing and analysing mobility data

Duration: 2023–2027

Coordinator: Aline Carneiro Viana

Other partners: UGE, IFPEN, IGN, CEREMA, INRIA (AGORA, ASCII, COATI, FUN, TRIBE)

Budget: 4 333 114€ INRIA (1 385 520,58€), TRiBE (766 500,24€)

Web link: Mob Sci-Dat Factory website

Abstract: Mob Sci-Data Factory shares the PEPR's primary goal of contributing to developing more sustainable mobility strategies by providing decision-making support methodology and a digital toolbox fed by appropriately selected and processed mobility data and by a deeper understanding of the involved transport uses and behaviors in mobility. This project will clarify and extract the elements determining and explaining the characteristics of mobility data, which also raise the following questions:

- What data and what are their availability, accessibility, quality, and representativeness?
- Which methods and digital tools are necessary for processing, calibrating, understanding, and enriching data while dealing with missing data and new acquiring?
- What are the specifications of the decision-support platform required for standard tools and data research sharing?

Answering those three questions together is a challenging task and the primary goal of Mob Sci-Data Factory project. Mob Sci-Dat Factory will make available in a secure and privacy-compliant cloud-based infrastructure different sources of mobility data together with open-source libraries and methods designed to be unified, modular, and interoperable from conception. Mob Sci-Dat Factory outcomes will facilitate data sovereignty and open-source development interoperability across multiple scientific actors in France, while accelerating research focused on mobility by offering privacy-compliant and secure data accessibility

10.5 Regional initiatives

AI4Demand-Responsive Transit (2024–2027)

Participants: Aline Carneiro Viana, Mohamed Ourahou.

Title: Geostatistical and Machine Learning Methods for Sustainable Deployment of Mobility on Demand (DIM AI4IDF - Intelligence Artificielle centrée sur l'humain en Ile de France)

Coordinator: TPT-IPP

Partners: TRiBE, PADAM Mobility. **From TRiBE**: A. Carneiro Viana, M. Ourahou.

Grant: 3-y PhD scholarship (Call: DIM AI4IdF).

Description: Mobility on Demand (MoD) services adapt vehicle routes to user requests, focusing on improving accessibility rather than just efficiency metrics. Accessibility measures opportunities (jobs, schools, shops) reachable within a set time, promoting social, economic, and environmental sustainability. It aims to leverage Mobility on Demand to reduce accessibility gaps between city centers and suburbs.

Team contribution: investigations on how Demand-Responsive Transit can improve accessibility in specific areas by evaluating the brought additional opportunities reachable within a limited time frame.

11 Dissemination

11.1 Promoting scientific activities

11.1.1 Scientific events: organisation

General chair, scientific chair

- Cédric Adjih:
  - co-chair of the CEFIPRA Indo-French joint workshop which took place at Inria Saclay, October 9-11, 2024.
  - co-chair of the 4th Workshop on IoT & Emerging Technologies, Sousse, Tunisia, 29-31 Oct. 2024.

Member of the organizing committees

- Amira Dhaouadi, Mehdi Sofiane Debbah and Nadjib Achir: Part of the organization committee of the CEFIPRA Indo-French joint workshop which took place on October 2024.
- Cédric Adjih: member of the Steering Comittee of PEMWN 2024.

11.1.2 Scientific events: selection

Chair of conference program committees

- Nadjib Achir: TPC co-chair of the 2nd IEEE Virtual Conference on Communications (IEEE VCC). The IEEE Communications Society created this event to allow worldwide researchers and students who cannot travel to traditional conferences because of visa issues, travel problems, or financial difficulties to present their recent scientific results and engage in conducive interactive discussions with fellow researchers working in their fields. The conference was held from the 3rd to the 5th of december 2024.

Member of the conference program committees

- Nadjib Achir: TPC member of IEEE VCC 2024, Vehiclouds 2024, CSNet 2024, PIMRC 2024.
- Aline Carneiro Viana: TPC member of IEEE WoWMoM 2024, Algotel 2024;
- Cédric Adjih: Reviewer of ICC 2024, PEMWN 2024.

11.1.3 Journal

Member of the editorial boards

- Aline Carneiro Viana: (Since 2024) Associate editor of EPJ Data Science; (Since 2014) For 10 years, Area editor of ACM SIGCOMM Computer Communication Review.

Reviewer - reviewing activities

- Nadjib Achir: Reviewer for Pervasive and Mobile Computing Journal, Computer Networks Journal.
- Aline Carneiro Viana: Reviewer of ACM SIGCOMM CCR, EPJ Data Science, IEEE/ACM Transactions on Networking.

11.1.4 Invited talks

- Philippe Jacquet: Talk at the Jacques Morgenstern Colloquium, which took place in December 2024 in Sophia Antipolis: "The performance paradoxes of wireless networks due to physical constraints". Keynote on "The Energy Differentiated Field Theorem: A Powerful Tool to Quantify Wireless Capacity Limits" at Indo-French Seminar on 6G Wireless Networks Oct 2024.
- Emmanuel Baccelli: Talk on "Some Embedded Software Trends" (STMicroelectronics Tech Council, 2024).
- Emmanuel Baccelli: Talk on low-power IoT cybersecurity and future-proofing RIOT at Open Source Experience and SIDO Paris (VivaTech, June 2024).
- Nadjib Achir: Keynote on "Privacy-aware passive sniffing: from wireless measurements to bounded trajectories" at the second Workshop on IoT and Emerging Technologies IoT & ET, Hammamet, Tunisia, April 2024.
- Aline Carneiro Viana: Invited as a keynote speaker for the EAI INTSYS 2024 conference but had to withdraw four weeks before the event due to medical reasons.
- Cédric Adjih: Invited as speaker at the NICT-Inria workshop in Tokyo, Japan, July 2024.

11.1.5 Scientific expertise

- Nadjib Achir served as a project expert for the CEFIPRA Program.

11.1.6 Research administration

- Emmanuel Baccelli Scientific Director of Inria Berlin.
- Aline Carneiro Viana is the leader of the TRiBE Project-Team of Inria since its creation (Jul.2019)
- Aline Carneiro Viana is the coordinator of ANR MITIk (since 2020-2025) and PEPR MOBIDEC Mob Sci-Data Factory (PC3, 2023-2027) projects.
- Nadjib Achir is the coordinator of the STIC AmSud LINT (2023-2024)
- Nadjib Achir is the co-pilot of PEPR NF FITNESS.

11.2 Teaching - Supervision - Juries

11.2.1 Teaching

- Nadjib Achir served as an associate professor at Sorbonne Paris Nord University until August 31, 2024, where he was fully dedicated to his duties at the university's Engineering School. He also led the third year of the "Télécommunications et Réseaux" specialty at the SupGalilée engineering school.
- Cédric Adjih: 12h *"Internet of Things"* lab sessions in 2024 at ENSEA
- Emmanuel Baccelli: *"IoT & Security"* seminar of *16-hours*, for *Master* student at Freie Universität Berlin in 2024.
- Amira Dhaouadi: Teaching assistant in Machine Learning for the CS department at LIX (Ecole Polytechnique-IPP) (2024-2025).

11.2.2 Supervision

- PhDs supervision (in progress):
  - Mohramed Ourahou (CIFRE)"Transport on Demand (ToD) guided by ML for maximizing the accessibility of territories", since Sep. 2024. Advisors: Aline Carneiro Viana, Andrea Araldo (TSP), Louis Zigrand (PADAM Mobility).
  - Wendlasida Ouedraogo, "Vers l'exploitation des réseaux hétérogènes", since january 2024. Advisors: Nadjib Achir, Lucas-Brehon Grataloup (IMT), Antoine Lavignotte (IMT) and Andrea Araldo (IMT).
  - Amira Dhaouadi, "Split computing for constrained devices", since january 2024. Advisors: Cédric Adjih and Nadjib Achir.
  - Rosario Patane, "VehiCloud: How can Vehicles increase Cloud intelligence?", since Dec. 2021. Advisors: Lila Boukhatem (Paris-Saclay), Andrea Araldo (IMT), Nadjib Achir .
  - Lucas Airam Castro de Souza, "Anomaly Detection for Vehicular Networks", since Nov. 2023. Advisors: Miguel Elias Mitre Campista, and Luís Henrique Maciel Kosmalski Costa (GTA, UFRJ), and Nadjib Achir. This Phd started at the UFRJ and co-supervision agreemed must be set up in 2024.
  - Saeed Alsabbagh (UVSQ), "Security of V2X Communications in 5g networks", since Sep. 2022. Advisors: N. Aitsaadi, C. Adjih and A. Adouane.
  - Felix Marcoccia (CIFRE) "Study of MANET Solutions for a Radio Communication System Based on Artificial Intelligence Algorithms", since 2022. Advisors: Paul Mühlethaler and Cédric Adjih.
  - Najoua Benalya (ENSI), "Agriculture de précision dans l'ère des drones et d'intelligence artificielle", since Nov. 2021. Advisors: I. Amdouni, A. Laouiti, L. Saidane, C. Adjih.
  - Khouloud Hwerbi (ENSI), "Optimized Architectures and Algorithms for Blockchain and IoT-based Applications", since Nov. 2021. Advisors: I. Amdouni, A. Laouiti, L. Saidane, C. Adjih.

  - Lucas Gabriel Da Silva Felix (Thalès CIFRE, Inria AIO, Inria TRiBE), “Machine Learning applied to graph topology and efficient pathing for mobile networks”, since 2022. Advisors: P. Mühlethaler, C. Adjih.
  - Haron C. Fantecele (LNCC, Brazil), “Mathematical modeling and machine learning applied to human mobility prediction”, since Feb. 2020. Advisor: Aline C. Viana and Antonio Tadeu (LNCC).
  - Emanuel Lima (half-time PhD, Univ. of Porto, Portugal), “Human Mobility Support for Personalised Data Offloading”, since 2017. Advisor: Ana Aguiar (Univ. of Porto). Collaborator: Aline Carneiro Viana.
  - Corentin Gautier (CIFRE) “FANET for Vehicle Swarms”, since 2022. Advisors: Paul Mühlethaler and Cédric Adjih.

- Master supervision:
  - the team regularly hosts master students and PhD interns for periods of 3 to 6 months. The list of students/interns concerned by this report year is mentioned in team members list.
  - In particular, Joao Paulo Esper, co-advised by Aline Carneiro Viana and Jussara Almeida (UFMG, Brazil), did a 2-year Master program from Jan. 2023 to Nov. 2024 and worked on ”Understanding Factors that Impact Individual Mobility Prediction with Federated Learning”. Outcomes were published at the ACM SIGSpatical 2024 conference [29].
  - Yijie Luo, advised by Cédric Adjih, on “Study of Neural Networks (State Space Models) adapted to the IoT ”

11.2.3 Juries

- Aline Carneiro Viana: **Selection committees:** for Inria Researchers with disabilities (CRCN-TH, *Chercheur/Chercheuse en situation de Handicap*); for Associate Professor at University of La Rochelle; for Full Professor (*repyramidage* committee) at Paris-Saclay University. **HDR juries:** W. Bechkit (INSA Lyon, May 2024), P. B. Velloso (CNAM, Dec. 2024). **PhD juries:** J. Koteich (FUN/INRIA, Univ. de Lille, Sep. 2024), M. P. Samuel (PRIVATICS/Inria, INSA-Lyon, Sep 2024).
- Cédric Adjih: **Selection committees: PhD juries:** Joe Saad (UVSQ, March 2024), Alix Jeannerot (INSA Lyon, Dec 2024). **PhD :**

11.3 Popularization

11.3.1 Productions (articles, videos, podcasts, serious games, ...)

- Aline Carneiro Viana and Nadjib Achir have participated of the *”L’esprit sorcier”* channel seeking to elucidate scientific inquiries with the input of experts from prominent French public research institutions. The scientific context was *”Human mobility and its impact on network ressources”* (**2.6K views in 8 months**), where the ANR MITIK project was also presented. Video released on April 26th, 2024.

12 Scientific production

12.1 Major publications

[1] L. Amichi, A. Carneiro Viana, M. Crovella and A. A. F. Loureiro. ‘Revealing an inherently limiting factor in human mobility prediction’. In: *IEEE Transactions on Emerging Topics in Computing* (2022). DOI: 10.1109/TETC.2022.3229088. URL: https://inria.hal.science/hal-03905517. In press.

[2] S. Banerjee, D. Barthel, Q. Lampin, M. Dumay, S. Coutant, C. Adjih, P. Muhlethaler and T. Watteyne. ‘Automated Header Compression in Constrained Networks’. In: *IEEE Communications Standards Magazine* (1st Oct. 2024). URL: https://inria.hal.science/hal-04618224. In press.

[3] N. Benalaya, I. Amdouni, C. Adjih, A. Laouiti and L. A. Saidane. 'Deep reinforcement learning approach for UAV search path planning in discrete time and space'. In: *IWCMC 2024 - The 20th International Wireless Communications and Mobile Computing*. The 20th International Wireless Communications and Mobile Computing (IWCMC). Ayia Napa, Cyprus: IEEE, 17th July 2024, pp. 1437–1442. DOI: 10.1109/IWCMC61514.2024.10592510. URL: https://inria.hal.science/hal-04836227.

[4] L. A. Castro de Souza, G. Franco Camilo, G. A. Fontes Rebello, L. C. de Brito Guimarães, M. E. M. Campista and L. H. Maciel Kosmalski Costa. 'Blockchain-based Approaches for Secure Federated Learning'. In: BRAINS 2024 - 6th Conference on Blockchain Research & Applications for Innovative Networks and Services. Berlin, Germany, 9th Oct. 2024. URL: https://hal.science/hal-04739271.

[5] L. A. Castro de Souza, M. Sammarco, N. Achir, M. E. M. Campista and L. H. Maciel Kosmalski Costa. 'AutoMHS-GPT: Automated Model and Hyperparameter Selection with Generative Pre-Trained Model'. In: CloudNet 2024 - IEEE International Conference on Cloud Networking. Rio de janeiro, Brazil, 27th Nov. 2024. URL: https://hal.science/hal-04739249.

[6] P. Cruz, N. Achir and A. Carneiro Viana. 'On the Edge of the Deployment: A Survey on Multi-Access Edge Computing'. In: *ACM Computing Surveys* 55.5 (2022), pp. 1–34. DOI: 10.1145/3529758. URL: https://inria.hal.science/hal-03637105.

[7] J. P. Esper, A. C. Viana and J. M. Almeida. 'Beauty or beast: human behavioral insights and learning power of federated mobility prediction'. In: *ACM SIGSPATIAL 2024*. ACM SIGSPATIAL - 32nd International Conference on Advances in Geographic Information Systems. Atlanta, United States, 1st Nov. 2024, pp. 325–337. DOI: 10.1145/3678717.3691323. URL: https://inria.hal.science/hal-04729716.

[8] I. Hmedoush, C. Adjih, P. Mühlethaler and L. Salaun. 'Multi-Power Irregular Repetition Slotted ALOHA in Heterogeneous IoT networks'. In: *PEMWN 2020 - 9th IFIP/IEEE International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks*. PEMWN 2020 - 9th IFIP/IEEE International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks, Berlin / Virtual, Germany, Dec. 2020. URL: https://hal.archives-ouvertes.fr/hal-03043850.

[9] Z. Huang, A. Tousnakhoff, P. Kozyr, R. Rehausen, F. Bießmann, R. Lachlan, C. Adjih and E. Baccelli. 'TinyChirp: Bird Song Recognition Using TinyML Models on Low-power Wireless Acoustic Sensors'. In: IS2 2024 - IEEE 5th International Symposium on the Internet of Sounds. Erlangen, France: IEEE, 30th Sept. 2024, pp. 1–10. DOI: 10.1109/IS262782.2024.10704131. URL: https://inria.hal.science/hal-04814457.

[10] P. Jacquet. 'Information Theoretic Study of Covid 19 Genome'. In: *Entropy* 26.3 (1st Mar. 2024), p. 223. URL: https://hal.science/hal-03546087.

[11] A. J. Kouam, A. Carneiro Viana and A. Tchana. 'Battle of Wits: To What Extent Can Fraudsters Disguise Their Tracks in International bypass Fraud?' In: ACM ASIACCS 2024 - 19th ACM Asia Conference on Computer and Communications Security. Singapore, Singapore, 1st July 2024. DOI: 10.1145/3634737.3657023. URL: https://hal.science/hal-04543435.

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12.2 Publications of the year

International journals

[18] S. Banerjee, D. Barthel, Q. Lampin, M. Dumay, S. Coutant, C. Adjih, P. Mühlethaler and T. Watteyne. 'Automated Header Compression in Constrained Networks'. In: *IEEE Communications Standards Magazine* (1st Oct. 2024). URL: https://inria.hal.science/hal-04618224. In press (cit. on p. 18).

[19] I. Cardoso-Pereira, J. B. Borges, A. Carneiro Viana, A. A. F. Loureiro and H. S. Ramos. 'POPAyI: Muscling Ordinal Patterns for low-complex and usability-aware transportation mode detection'. In: *IEEE Internet of Things Journal* 11.10 (25th Jan. 2024), pp. 17170–17183. URL: https://inria.hal.science/hal-04417507. In press (cit. on p. 24).

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[23] A. K. Mishra, A. Carneiro Viana and N. Achir. 'Bleach: From WiFi probe-request signatures to MAC association'. In: *Ad Hoc Networks* 164 (Nov. 2024), p. 103623. DOI: 10.1016/j.adhoc.2024.103623. URL: https://hal.science/hal-04732154 (cit. on p. 21).

International peer-reviewed conferences

[24] N. Benalaya, I. Amdouni, C. Adjih, A. Laouiti and L. A. Saidane. 'Deep reinforcement learning approach for UAV search path planning in discrete time and space'. In: *IWCMC 2024 - The 20th International Wireless Communications and Mobile Computing*. The 20th International Wireless Communications and Mobile Computing (IWCMC). Ayia Napa, Cyprus: IEEE, 17th July 2024, pp. 1437–1442. DOI: 10.1109/IWCMC61514.2024.10592510. URL: https://inria.hal.science/hal-04836227 (cit. on p. 29).

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[26] L. A. Castro de Souza, M. Sammarco, N. Achir, M. E. M. Campista and L. H. Maciel Kosmalski Costa. 'AutoMHS-GPT: Automação de Seleção de Modelos e Hiperparâmetros por meio de Modelo Generativo para Detecção de Anomalias em Redes Veiculares'. In: SBRC 2024 - 42° Simpósio Brasileiro de Redes de Computadores e Sistemas Distribuídos. Niteroi, Universidade Federal Fluminense, Brazil, 20th May 2024. URL: https://hal.science/hal-04739233 (cit. on p. 30).

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[30] L. G. S. Félix, A. J. Kouam, A. Carneiro Viana, N. Achir and J. M. Almeida. 'The Silent Signature: Behavior-based User Exposure in Mobility Data'. In: MDM 2025 - 26th IEEE International Conference on Mobile Data Management. Irvine (CA), United States, 2nd June 2025. URL: https://hal.science/hal-05057826.

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[32] K. Hwerbi, I. Amdouni, C. Adjih, P. Jacquet, L. A. Saidane and A. Laouiti. 'Delay analysis of a mempool-based blockchain protocol under asymptotic hypothesis'. In: *PEMWN 2024 : 13th IFIP/IEEE International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks*. 13th IFIP/IEEE International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks (PEMWN). Agadir, Morocco: IEEE, 31st Oct. 2024. DOI: 10.23919/PEMWN62766.2024.10737565. URL: https://inria.hal.science/hal-04836101 (cit. on p. 34).

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[39] F. Molano Ortiz, A. K. Mishra, F. D. de M. Silva, A. Fladenmuller and L. H. M. K. Costa. 'Collecte de traces WiFi publiques: de la protection de la vie privée à l'analyse de trajectoires'. In: *CoRes 2024: 9èmes Rencontres Francophones sur la Conception de Protocoles, l'Évaluation de Performance et l'Expérimentation des Réseaux de Communication*. CoRes 2024 - 9èmes Rencontres Francophones sur la Conception de Protocoles, l'Évaluation de Performance et l'Expérimentation des Réseaux de Communication. Ed. by N. Achir and A. Carneiro Viana. Saint-Briac-sur-Mer, France, 2024, pp. 1–4. URL: https://hal.science/hal-04568193 (cit. on p. 21).

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