RESEARCH CENTRE

Inria Saclay Centre

2023 ACTIVITY REPORT

Project-Team TRIBE

inTeRnet BEyond the usual

DOMAIN

Networks, Systems and Services, Distributed Computing

THEME

Networks and Telecommunications

Inria

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Project-Team TRIBE

Creation of the Project-Team: 2019 June 01

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Computer sciences and digital sciences

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2 Overall objectives

2.1 Vision and approach

TRiBE stands for “Internet Beyond the Usual” and belongs to the Inria theme “Networks and Telecommunications” as well as contributes to the “Challenge no 11: Toward a trustworthy Internet of Everything” of the strategic plan of Inria. *Building on an approach combining protocol design, data analytics, and experimental research, the research contributions of TRiBE aim at contributing to the design of smart, unified, and tactful Internet edge networks, skilled for answering applications, services, or end-users' purposes.*

All the emerging IoT specificities and requirements (i.e., heterogeneity of devices and services, densification, traffic growth, ubiquitous cyber-physical context, etc) bring new demands and consequently, new scientific and technological challenges to the edge of the Internet. In this context, our conviction is that the success of the Internet of Things is rooted: in the **network design's choices** involving the devices,

in the **intelligence of the protocols and associated services** as well as in the **capability of reaction and adaptation** of the edge-core network's communication loop.

Toward this belief, we base our approach on the combination of protocol design, data analysis, and experimental research, while meeting the requirements and challenges brought by the IoT to the edge of the Internet. Therefore, the research of TRiBE is organized around the following research directions:

- **Technologies for accommodating low-end IoT devices:** 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:** we focus on learning the behaviors of high-end IoT devices, the smart devices. More specifically, the idea is to take advantage of the "how in the spatiotemporal scale" and the "for what purpose" these devices are used. This brings the human element into play, which dynamics are shaping the way their smart devices are interacting with the edge of the Internet and, consequently, are requesting and consuming network resources and services.
- **Technologies for edge-core network interaction:**This element closes the *network* ↔ *usability* ↔ *device* ↔ *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 directions will contribute to our vision toward a **Smart, Unified, and Tactful Internet edge skilled for answering the application, services, or end-users' purposes.**

2.2 New challenges

The Internet has steadily evolved over the past decades from a small homogeneous to a gigantic Internet of Things (IoT) interconnecting an extremely wide variety of machines (e.g., PCs, smartphones, sensors/actuators, smart appliances, smart vehicles), and providing an extremely wide variety of services. Globally, devices and connections are growing faster than both the population and Internet users, as foreseen by Cisco. Forecasts mention an IoT market that will attain a compound annual growth rate of 28.5% from 2016 to 2020 as well as an installed base of IoT devices of over 75.4B devices by 2025. Added to these statistics is the fact that global mobile data traffic will grow nearly twice as fast as fixed IP traffic from 2017 to 2022: Smartphones account for most of this growth.

Hence, the edge of this network now consists of dense deployment of machines ranging from PCs to smartphones, from sensors/actuators to smart appliances, and from smart vehicles to diverse kinds of robots. As a consequence, humans are immersed in a highly connected and ubiquitous cyber-physical context, and as end-users of the network and its numerous services, their satisfaction has become the main focus.

In this context, the IoT is simultaneously used as a tool to gather more data, and as a means to automate more advanced control. Some businesses and institutions aim to gather more data to better understand their customers, so as to improve services. Other efforts aim to further immerse their customers into a flourishing, integrated cyber-physical environment, which can automatically and optimally adapt to their needs. All these emerging IoT-related opportunities bring new requirements and consequently, new scientific and technological challenges to the edge of the Internet.

First, the densified deployment of heterogeneous **low-end IoT devices** (e.g. sensors, actuators, etc.) at the edge of the Internet requires dealing with (1) the accommodation of machines with extremely limited capabilities, with a primary focus on low power requirements while (2) allowing their seamless integration in interoperable systems (often using IP as a common factor).

Second, today's pervasiveness of **high-end IoT devices** (e.g. smart handheld devices) distribute increasing capabilities (i.e., processing, storage, connectivity) at the edge of the network, and make our real-life and virtual activities seamlessly merge together. In this domain, we need a better understanding

of: (1) when, where, and for what the high-end IoT devices are used, (2) how the uses vary among individuals, and (3) how social norms and structure dictate individuals' behavior influence the way they interact with network services and demand resources.

Related to the challenge hereabove, people's mobility and activity patterns are general in nature, and similarities emerge in different cities worldwide. The analysis of these patterns reveals many interesting properties of human mobility and activity patterns. While all these properties have been investigated at length, the COVID-19 pandemic highly perturbed our mobility patterns and use of urban spaces. This raises important questions: (1) how mobility patterns at an urban scale were affected by the pandemic; (2) can the modeling of such patterns provide a clear association with an epidemic spread, such as COVID-19 in different areas of a city?; last but not least, (3) can we still recommend safe outdoor path inside cities in order to limit the exposure to virus propagation? The 1st question answer is also closely related to the changes in "how" and "where" network resources were demanded.

The research contributions of TRiBE aim at dealing with such requirements and challenges brought to the Internet's edge. One should design adapted algorithms and communication mechanisms and network users' behavior modeling for addressing such challenges while leveraging the new technological opportunities brought by the Internet of Things.

3 Research program

3.1 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 is expected to gradually connect billions of low-end devices to the Internet, and thereby drastically increase communication without human source or destination. Low-end IoT devices differ starkly from high-end IoT devices in terms of resources such as energy, memory, and computational power. Projections show this divide will not fundamentally change in the future and that IoT should ultimately interconnect a dense population of devices as tiny as dust particles, feeding off ambient power sources (energy harvesting). These characteristics constrain the software and communication protocols running on low-end IoT devices: they are neither able to run a common software platform such as Linux (or its derivatives), nor the standard protocol stack based on TCP/IP. Solutions for low-end IoT devices require thus: **(i) optimized communication protocols** taking into account radio technology evolution and devices constrained requirements; **(ii) tailored software platforms** providing high-level programming, modular software updates as well as advanced support for new security and energy concentration features; **(iii) unification of technologies** for low-end IoT, which is too fragmented at the moment, guaranteeing integration with core or other edge networks.

- **[Axis 2] Technologies for leveraging high-end IoT devices' advents:** High-end IoT devices are one of the most important instances of connected devices supporting a noteworthy shift towards mobile Internet access. As our lives become more dependent on pervasive connectivity, our social patterns (as human beings in the Internet era) are nowadays being reflected from our real life onto the virtual binary world. This gives birth to two tendencies. From one side, edge networks can now be utilized as mirrors to reflect the inherent human dynamics, their context, and interests thanks to their well-organized recording and almost ubiquitous coverage. On the other side, social norms and structures dictating human behavior (e.g., interactions, mobility, interest, cultural patterns) are now directly influencing the way individuals interact with network services and demand resources or content. In particular, we observe the particularities present in human dynamics *shape the way (i.e., where, when, how, or what) resources, services, and infrastructures are used at the edge of the Internet.* Hence, we claim a need to digitally study high-end IoT devices' end-users behaviors and to leverage this understanding in networking solutions' design, so as to optimize network exploitation. This suggests the **integration of the heterogeneity and uncertainty of behaviors in designed networking solutions**. For this, *useful knowledge* allowing the understanding of behaviors and

context of users has to be *extracted and delivered out* of large masses of data. Such knowledge has to be then *integrated into current design practices*. This brings the idea of a more *tactful networking design practice* where the network is assigned with the human-like capability of observation, interpretation, and reaction to daily life features and entities involving high-end IoT devices. Research activities here include: **(i) the quest for meaningful data**, which includes the integration of data from different sources, the need for scaling up data analysis, the usage and analysis of fine-grained datasets, or still, the completion of sparse and coarse-grained datasets; **(ii) expanding edge networks' usage understanding**, which concerns analysis on how and when contextual information impact network usage, fine-grained analysis of short-term mobility of individuals, or the identification of patterns of behavior and novelty-seeking of individuals; **(iii) human-driven prediction models**, extensible to context awareness and adapted to individuals preferences in terms of novelty, diversity, or routines. Finally, the current epidemic crises also showed a new potential impact of mobility's understanding and patterns modeling: such investigation can potentially provide a clear association with the epidemic spread (e.g., such as COVID-19) in different areas of a city.

- **[Axis 3] Articulating the IoT edge with the core of the network:** The edge is the interface between the IoT devices and the core network: some of the challenges encountered by IoT devices have their continuity at the edge of the network inside the gateway (i.e., interoperability, heterogeneity and mobility support). Besides, the edge should be able to support intermediary functions between devices and the rest of the core (e.g., the cloud). This includes: **(i) proxying functionality**, facilitating connections between devices and the Internet; **(ii) machine learning enhanced IoT solutions**, designed to improve the performance of advanced IoT networked systems (e.g., through methods such as supervised, unsupervised or reinforcement learning) at adapted levels of the protocol stack (e.g., for multiple access, coding, choices); **(iii) IoT data contextualization**, so that the collection of meaningful IoT data (i.e., right data collected at the right time) can be earlier determined closer to the data source; **(iv) intermediary computation** through fog or Mobile Edge Computing (MEC) models, where IoT devices can obtain computing, data storage, and communication means with lower latency in a decentralized way; or **(v) security of end-to-end IoT software supply-chain**, including remote management and over-the-air updates.

4 Application domains

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

- **Research domains:** Computer science, Mobile wireless networks, Internet of Things, Tactile Internet, Human mobility analytics and prediction, Edge smart resource allocation, IoT software design, Social network, Energy saving, Mobility-aware networking solutions.
- **Tactile Internet:** considered the next evolution of the Internet of Things (IoT), related applications are the ones combining ultra-low latency with extremely high availability, reliability and security. They will demand smart interaction between individuals-to-devices and devices-to-devices, enabling real-time and reliable interaction in industrial, societal and business use cases. Application examples are: Automation and Smart Transportation, 3D and educational games, x-reality applications and services, etc. Our solutions aim 1) to bring intelligence and just-in-time adaptivity (to individuals' behaviors, IoT limitations, and context of services and environment) to networking's resource allocation, management, and usability, and 2) to contribute to Tactile Internet goals.
- **IoT twins:** The rise of IoT will lead to the emergence of digital twins (or copies) of complex systems, manageable via 5G or further generations of digital networks. Examples of digital twins are those copying and showing digital information (i.e., relative to working/leisure areas, traffic/road/weather conditions, air quality, state of plantations/forests, etc.) of a city, a region, or even a county. Such digital copies will be highly distributed complex systems that require a solid and reactive blockchain system. Such a blockchain system is expected to manage data flows from several hundred million sensors, also scheduled to occur at very high frequency. Our solutions related to IoT-massive edges

and applications, analytic learning theory, and frugal AI aim to support the development of such applications. Digital twins showing information related to traffic, transportation, or visitation of geographical areas will also require the understanding and modeling of the mobility-life of a population and the space frequentation it generates. Our solutions on mobility understanding, profiling, and reproduction have the potention to support the advances of such type of digitatl twins.

- **Urban planning and disaster management applications:** The team has activities bringing insights to such types of applications. Those are related to our research topics on *"SafeCityMap: From spatiotemporal mobility of our society to the COVID propagation understanding"* and on *"Geometry of virus exposure"*, both detailed in "New Results" section. Generally speaking, mobility analytics present on these two topics, bring an understanding of the urban space usability, which can indeed be used for epidemic prevention, but also for disaster response and urban traffic management. These analytics also have the potential to improve mobility anticipation algorithms and quality of services offered by pervasive computing applications. Another application is the provision of energy-efficient and cost-effective network infrastructures, adapted to the modified population mobility patterns. As a final applicability, our investigations and designed tools bring solutions to study the spatiotemporal activity of geographical areas (e.g., visitation rate, frequentation patterns, etc) and consequently, to understand the socio-economic impact that activity-like, residential, or any-type areas are subject to (i.e., in spetial during particular situations, such as the lockdown preriods).

- Other applications that impacted our research are also discussed in the Social and Environmental responsibility (next section).

5 Social and environmental responsibility

5.1 Footprint of research

Our research activities are not expected to impact the environment, since we work on algorithm design and software editing. Our experiments are not going beyond extremely short-scale lab experiments. The IT activities that are most likely to impact the climate are massive data stored in data centers, bitcoin mining and heavy deep learning training and we are not practicing any of them (though we plan to do some distributed machine learning for optimizing protocols).

Furthermore, we believe our research can positively impact society and the environment. This belief is due to the following ascertainments, which naturally conduct our research and our envisaged outcomes.

Assertion: The energy efficiency in the ICT and data centers sectors is considered a key part of the energy and climate targets for 2020-2030, of the European energy policies. The high energy consumption (past and forecasted future: forecasted to consume 13% of the worldwide electricity by 2030) is due not only to the in-expansion electricity needs of technological advances (e.g., data centers, new traffic demand, and connected devices) but also due to the energy-harmful over-provisioning tendency in the ICT sector.

For example, from one side, the community agrees there is a limit on how far energy-efficient data centers could go. This limitation calls for a new architectural paradigm, where Internet intelligence should move from centralized computing facilities to distributed and in-network computation. Still, the very fast-growing trend at the Internet edge (kept by the different types and capabilities of IoT devices and consequently, by their communication needs) accelerates the unprecedented proliferation of new performance-hungry IoT applications and services. Such devices will require increasing computational power and will be more power-hungry than ever.

On the other hand, considering smart devices inherit the dynamics and the decision-making of their users, mobility and heterogeneous behavior of individuals add uncertainties on where and when network resources will be needed. The standard practice in the current Internet to tackle this instability has been the any-and-anywhere extra-supplying of resources in the network. Nevertheless, in an Internet that has become essentially mobile, such over-provisioning will make energy consumption rapidly inflate, which becomes too costly and a practice that asks for revision.

Another growing priority is related to climate changes. The European Green Deal (2019) aims to suppress net greenhouse gas(GHG) emissions by 2050, where transport accounts for a quarter of such emissions in Europe. Besides, the European Commission has also recently set out its *Sustainable and Smart Mobility Strategy* (2020), considering that the success of the European Green Deal will depend on our ability to make the transport system sustainable as a whole. This radically affects the way we look at (i) the transport usability and availability, (2) at the mobility of people, as well as (3) at their relationship to spatial dynamics, emphazing the importance in understanding the determinants of mobility behaviour and the drivers of change.

TRiBE environmental responsibilities:

- TRiBE research is naturally targetting a scenario where network intelligence is pushed 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) provide 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 (2) 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**, 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**.

- **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. Moreover, by making complex computations feasible on IoT devices and at the edge, we avoid inefficiencies in transmitting information back and forth.

- As a result of TRiBE engagement in EU environment and green priorities, the team is strongly involved in two national research actions (**PEPR**): (1) the MOBIDEC (i.e., *Digitalisation et Décarbonation de Mobilités*) focusing on the digital and carbon neutrality of mobility and (2) the *5G et Réseaux du Futur* aiming the acceleration of advanced 5G and future networks. Both PEPRs and consequently, the contributions of the team on such actions, will contribute to make research impacting 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 reseach axis.**

5.2 Impact of research results

The rise of the Internet of Things will naturally lead to an increase by a significant factor: the number of connected devices. This *a priori* would negatively impact the environment since it would multiply the power consumption of networks. Nevertheless, one of the main IoT applications is the control of the environment by monitoring and curing critical environmental situations. Most of them would be low-powered wireless low-end devices, which are very likely powered by solar energy sources. Our research focuses **(1) on the optimization and standardization** of very efficient low-end networks, (2) **on the power usage contention** of high-end devices, and (3) **on the cost limitation** of creating a digital twin made of a sensor field by a green blockchain design. This second goal focuses on optimizing the

quantity of information device-local applications should move outside the Internet edge, such as for edge machine learning.

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) have 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 resource allocation for devices). The SafeCityMap [5] and Ariadne Covid Inria-Covid projects carried by members of the team reinforce such assertion. Other contributions such as [48, 46, 37, 36] demostrate the engagement of the team in **enforcing the carbon neutrality and the green management of mobility**.

In particular, the SafeCityMap project brings investigations on the impact of the 1st, 2nd, and 3rd lockdown on the regular mobility habits of the Paris population. Results of such investigations are periodically posted in the interactive webpage here: 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**.

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). 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.

When privacy concerns are identified, TRiBE has dedicated efforts in designing solutions to ensure anonymisation and/or fraud detection of wireless networks' datasets. Related to the anonimization concern, we point out important privacy-related flaws in current wireless communication standards [45]. Our related designed solutions highligh the possibility to efficiently (i) identify devices associated to randomised addresses and (ii) reconstruct their trajectories only based on signal measurements (cf. the PhD thesis of Abhishek Kumar Mishra [32]). On the other hand, the team contributions on cellular fraud dectection from datasets bring a deep understanding on the evolution of cellular frauds of SIMBox type and on the vulnerabilities of current related detection literature [43] (cf. the PhD thesis of Anne Josiane Kouam). By highlighting flaws and vulnerabilities of literature solutions, TRiBE brings contributions with a potential societal and economic impact.

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.

6 New software, platforms, open data

6.1 New software

6.1.1 Gardinet

Keyword: Distributed networks

Functional Description: Gardinet (previously DragonNet) is a generic framework for network coding in wireless networks. It is a initially result of the GETRF project of the Hipercom2 team.

It is based on intra-flow coding where the source divides the flow in a sequence of payloads of equal size (padding may be used). The design keys of DragonNet are simplicity and universality, DragonNet does not use explicit or implicit knowledge about the topology (such as the direction or distance to the source, the loss rate of the links, ...). Hence, it is perfectly suited to the most dynamic wireless networks. The protocol is distributed and requires minimal coordination. DragonNet architecture is modular, it is based on 5 building blocks (LIB, SIG, Protocol, SEW and DRAGON). Each block is almost independent. This makes DragonNet generic and hence adaptable to many application scenarios. DragonNet derives from a prior protocol called DRAGONCAST. Indeed, DragonNet shares the same principles and theoretical overview of DRAGONCAST. It enriches

DRAGONCAST by the information base and signaling required to perform broadcast in wireless networks and in wireless sensor networks in particular.

URL: http://gitlab.inria.fr/gardinet

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Participants: Antonia Masucci, Cédric Adjih, Hana Baccouch, Ichrak Amdouni

6.1.2 SWIF-codec

Name: An open-source sliding window FEC codec

Keyword: Error Correction Code

Functional Description: This development is done in the context of the "Coding for Efficient Network Communications" IRTF Research Group (NWCRG, [https://datatracker.ietf.org/rg/nwcrg]) and IETF hackathon.

This work has strong relationships with the Generic API I-D [https://datatracker.ietf.org/doc/draft-roca-nwcrg-generic-fec-api/] and RFC 8681 on RLC codes [https://www.rfc-editor.org/rfc/rfc8681] as examples of sliding window codes.

URL: https://github.com/irtf-nwcrg/swif-codec

Authors: Vincent Roca, Cédric Adjih, Oumaima Attia, François Michel

Contact: Vincent Roca

6.1.3 SimBle

Name: Simulating Privacy-Preserving Real-World BLE Traces

Keywords: Privacy, Simulation, Bluetooth

Functional Description: SimBle is the first BLE simulation stack capable of generating traces that preserve privacy. It introduces resolvable private addresses that are the core to BLE device and network privacy-provisions. It is capable of emulating the behavior of any real BLE device/hardware. Users have to choose the appropriate device class they want to test, based on the targeted device. It resolved the lack of ground truth for scalable scenarios after the introduction of MAC address randomization.

URL: https://gitlab.inria.fr/mabhishe/simble

Publications: hal-03906579v2, hal-03906600, hal-03298339v2, hal-03125920

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6.1.4 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.

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

6.1.5 FraudZen

Keywords: Simulation, SIMBox fraud, Fraud detection, Data analytics

Scientific Description: FraudZen is an open-source simulator of SIMBox fraud strategies and detection methods in LTE networks. It is designed to tackle the lack of fraudulent and up-to-date CDRs 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.

Functional Description: FraudZen is an open-source simulator of SIMBox fraud strategies and detection methods in LTE networks. It is designed to tackle the lack of fraudulent and up-to-date CDRs 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.

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

Publications: hal-03897099, hal-03838853, hal-03658019

Authors: Anne Josiane Kouam Djuigne, Alain Tchana, Aline Carneiro Viana

Contact: Aline Carneiro Viana

Partner: INP Grenoble

6.1.6 MITIK-MAN

Name: MITIK Data Collector Management Tools

Keywords: Wi-Fi, Infrastructure software, Mobile Crowdsensing

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-MAN is a management tool developed as part of the MITIK project and which 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 configuration of multiple collectors simultaneously. - Centralized management of several collectors (synchronization, raw data capture, data transfer and data processing...). - Configuration of parameters and execution of MITIK project modules.

Authors: Fernando Molano Ortiz, Aline Carneiro Viana, Nadjib Achir

Contact: Fernando Molano Ortiz

6.1.7 MITIK-HAND

Name: MITIK's data handling tool

Keywords: Wi-Fi, Trajectory Generation, Mobility

Functional Description: MITIK-HAND comprises two tools: 1. The first tool performs MAC association of randomized MAC addresses used by the same device from probe-requests. 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. 2. The second tool reconstructs a mobile terminal's trajectory by introducing the concept of bounded trajectory. 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.

URL: https://gitlab.inria.fr/fmorlano/mitik_data_handling

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

Contact: Fernando Molano Ortiz

6.1.8 MITIK-SENS

Name: Privacy-preserving WiFi Sniffer tool

Keywords: Wi-Fi, Privacy

Functional Description: Public wifi (IEEE802.11) 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.

URL: https://gitlab.inria.fr/achir/mitik-sens

Authors: Fernando Dias De Mello Silva, Fernando Molano Ortiz, Abhishek Mishra, Aline Carneiro Viana, Nadjib Achir

Contact: Fernando Dias De Mello Silva

6.2 New platforms

Open Experimental IoT Platforms

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

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, we plan to build upon the FIT IoT-LAB federated testbeds, that we have participated in designing and deploying recently. We plan to further develop FIT IoT-LAB with more heterogeneous, up-to-date IoT hardware and radios that will provide a usable and realistic experimentation environment. The goal is to provide a tool that enables testing a validation of upcoming software platforms and network stacks targeting concrete IoT deployments.

In parallel, 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 build 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, which we co-founded together with Freie Universitaet Berlin. The key challenge is to improve usability and add functionalities while maintaining architectural consistency and a small enough memory footprint. The goal is to provide an IoT software platform that can be used like Linux is used for less constrained machines, both (i) in the context of research and/or teaching, as well as (ii) in industrial contexts. Of course, we plan to use it ourselves for our own experimental research activities in the domain of IoT e.g., as an API to implement novel network protocols running on IoT hardware, to be tested and validated on IoT-LAB testbeds.

7 New results

7.1 Vehicular Networks [Axis 3]

7.1.1 Can Vehicular Cloud Replace Edge Computing? [Axis 3]

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.

7.1.2 Analyzing and Optimizing Extended-CAM Service Using Simple Stochastic Geometry Model [Axis 3]

Participants: Paul Mühlethaler *(Inria, AIO)*, Nadjib Achir.

Vehicular Ad hoc Networks (VANETs) offer a promising approach to enhancing road safety. Cooperative Awareness Messages (CAM) is an essential service in VANETs, allowing vehicles to transmit radio beacons containing their positions and velocities. These messages inform nearby vehicles about the traffic situation. This paper focuses on Extended Cooperative Awareness Messages (ECAM), which include additional information about nearby vehicles. ECAM beacons consist of a vehicle's speed, position, and data on the positions and velocities of other vehicles in its vicinity. This comprehensive information enables nearby vehicles to understand the traffic situation and take appropriate actions to prevent potential collisions. Studies demonstrate that ECAM has the potential to significantly improve road safety by providing comprehensive and up-to-date traffic information. This paper uses stochastic geometry to evaluate different versions of ECAM services and compare the results with simple simulations. The evaluation assumes random vehicle placement using a homogeneous Poisson Point Process and models the ECAM service using the Matern Point Process.

This article was published at PEMWN'23 [25].

7.1.3 5G V2X Misbehavior Detection as Edge Core Network Function based on AI/ML

Participants: Hadi Yakan *(Université Paris-Saclay, UVSQ, DAVID)*, Ilhem Fajjari *(Orange Innovation)*, Nadjib Aitsaadi *(Université Paris-Saclay, UVSQ, DAVID)*, Cedric Adjih.

As 5G Cellular Vehicle-to-Everything (C-V2X) technology takes the lead in V2X communication, it opens the possibility for telecommunication service providers to offer Vehicleto-Network (V2N) services using their existing 5G network infrastructure. To enhance the security of 5G V2N services, in this paper we propose a novel collaborative V2X misbehavior detection system. This system would safeguard the V2X application servers (V2X ASs), deployed in the 5G edge network, from any malicious V2X position manipulation attacks. Our proposal includes two enhanced machine learning models. The first model utilizes historical data to conduct On-Road Plausibility Checks (ORPC), while the second model builds

upon the first by enabling collaboration among edge detection nodes through the sharing of attack ratios for each vehicle. Our proposed models were tested using extensive 5G core-network emulations, yielding excellent results. The first model achieved a notable accuracy improvement from 73% to 91%, while the second model further enhanced the accuracy to an impressive 95%.

This article was presented at GLOBECOM'2023

7.1.4 Federated Learning for V2X Misbehavior Detection System in 5G Edge Networks

Participants: Hadi Yakan *(Université Paris-Saclay, UVSQ, DAVID)*, Nadjib Aitsaadi *(Université Paris-Saclay, UVSQ, DAVID)*, Ilhem Fajjari *(Orange Innovation)*, Cedric Adjih *(Inria Saclay)*.

The emergence of 5G Cellular Vehicle-to-Everything (C-V2X) has made it the predominant technology for enabling Vehicle-to-Everything (V2X) communications. As a result, this has created an opportunity for telecommunications service providers to leverage their pre-existing 5G network infrastructure, enabling them to provide Vehicle-to-Network (V2N) services. In this paper, we propose a new approach that enhances the security of 5G V2N services through the implementation of a Federated Learning V2X misbehavior de- tection system within the 5G core network. The proposed system aims to protect V2X application servers (V2X ASs) that are located in 5G edge networks against potential V2X attacks while leveraging the privacy and scalability advantages of Federated Learning. Our proposed model is compared, using extensive emulations, to other centralized and distributed approaches, achieving excellent results, which makes it feasible for deployment. Our proposal achieved a notable accuracy of 98.4%, while scoring an impressive 99.3% precision and 96.9% detection rate.

This article was presented at MSWiM'2023 and was the best paper runner-up.

7.2 Impact of User Privacy and Mobility on Edge Offloading [Axis 3]

Participants: Esper João Paulo *(Universidade Federal de Minas Gerais, Brazil)*, Nadjib Achir, Kleber Vieira Cardoso *(Universidade Federal de Goiás, Brazil)*, Jussara M. Almeida *(Universidade Federal de Minas Gerais, Brazil)*.

Offloading high-demanding applications to the edge provides better quality of experience (QoE) for users with limited hardware devices. However, to maintain a competitive QoE, infrastructure and service providers must adapt to users' different mobility patterns, which can be challenging, especially for location-based applications. Another issue that needs to be tackled is the increasing demand for user privacy protection. With less (accurate) information regarding user location, preferences, and usage patterns, forecasting the performance of offloading mechanisms becomes even more challenging. This work discusses the impacts of users' privacy and mobility when offloading to the edge. Different privacy and mobility scenarios were simulated and discussed to shed light on the trade-offs among privacy protection, mobility, and offloading performance.

This article was published at IEEE PIMRC'23 [16].

7.3 Modern Random Access: Irregular Repetition Slotted Aloha (IRSA) [Axis 1]

Participants: Iman Hmedoush, Cédric Adjih, Paul Mühlethaler *(Inria, EVA)*, Chung Shue Chen *(Nokia Bell Labs)*, Pengwenlong Gu.

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.

7.3.1 DS-IRSA: A Deep Reinforcement Learning and Sensing Based IRSA

Participants: Iman Hmedoush, Pengwenlong Gu, Cédric Adjih, Paul Mühlethaler.

One of the main difficulties to enable the future scaling of IoT networks is the issue of massive connectivity. Recently, Modern Random Access protocols have emerged as a promising solution to provide massive connections for IoT. One main protocol of this family is Irregular Repetition Slotted Aloha (IRSA), which can asymptotically reach the optimal throughput of 1 packet/slot. Despite this, the problem is not yet solved due to lower throughput in non-asymptotic cases with smaller frame sizes. In this paper, we propose a new variant of IRSA protocol named Deep-Learning and Sensing-based IRSA (DS-IRSA) to optimise the performance of IRSA in short frame IoTs, where a sensing phase is added before the transmission phase and users' actions in both phases are managed by a deep reinforcement learning (DRL) method. Our goal is to learn to interact and ultimately to learn a sensing protocol entirely through Deep Learning. In this way, active users can coordinate well with each other and the throughput of the whole system can be well improved. Simulation results show that our proposed scheme convergence quickly towards the optimal performance of almost 1 packet/slot for small frame sizes and with enough minislots and can achieve higher throughput in almost all cases.

This article [17] was presented at GLOBECOM 2003.

7.3.2 Breaking the Unit Throughput Barrier in Random Access Protocol-Based Distributed Systems

Participants: Parikshit Hegde, Akshit Kumar *(Columbia Business School, USA)*, Rahul Vaze *(TIFR Mumbai, India)*, Amira Alloum *(Qualcomm, France)*, Cédric Adjih.

A multi-level random power transmit strategy that is used in conjunction with a random access protocol (RAP) (e.g. ALOHA) is proposed to fundamentally increase the throughput in a distributed communication network. A SIR model is considered, where a packet is decodable as long as its SIR is above a certain threshold. In a slot chosen for transmission by a RAP, a packet is transmitted with a power level chosen according to a distribution, such that multiple packets sent by different nodes can be decoded at the receiver in a single slot, by ensuring that their SIRs are above the threshold with successive interference cancelation. The achievable throughput and the upper bounds are shown to be close with the help of comprehensive simulations. The main takeaway is that the throughput of more than 1 is possible in a distributed network, by using a judicious choice of power level distribution in conjunction with a RAP.

This paper was presented at the conference NCC 2023, Guwahati, India.

7.3.3 Impact of Nonlinear Power Amplifier on BER Performance of OTFS Modulation

Participants: Sanjeev Sharma *(IIT (BHU) Varanasi, India)*, Amit Singh *(IIT (BHU) Varanasi, India)*, Kuntal Deka *(IIT Guwahati, India)*, Cédric Adjih.

Recently, two dimensional orthogonal time frequency space (OTFS) modulation technique has introduced in wireless communications to combat the effects of multipath fading and Doppler spread. In this paper, we analyze the impact of nonlinear power amplifier (NPA) and phase noise on the OTFS system over the EVA channel model. The study focuses on the bit error rate (BER) performance concerning the input-back-off (IBO) and the nonlinearity parameter values of the NPA. The results demonstrate that both NPA and phase noise significantly degrade the OTFS system performance, especially for higher modulation schemes and low values of IBO. Furthermore, we numerically analyze the impact of system parameter variations on BER performance.

This work was presented at IEEE International Conference on Advanced Networks and Telecommunications Systems ANTS 2023.

7.3.4 Performance Analysis of Active Intelligent Reflecting Surface-Assisted System: BER and Sum-Rate Evaluation

Participants: Sanjeev Sharma *(IIT (BHU) Varanasi, India)*, Kuntal Deka *(IIT Guwahati, India)*, Cédric Adjih, Alok Kumar *(Jaypee University of Information Technology, Waknaghat, India)*.

The study introduces active intelligent reflecting surfaces (AIRS) as a solution to improve signal strength in wireless systems, overcoming the limitations of passive IRS (PIRS). AIRS amplifies and adjusts the phase of reflected signals, enhancing system performance. The research focuses on analyzing the bit error rate and sum-rate of an AIRS-assisted system, considering various factors like channel information and distance between components. Simulations reveal that AIRS significantly outperforms PIRS, especially in scenarios with a direct link. However, a highly equipped PIRS can approach AIRS's efficiency under certain conditions.

This work was presented at IEEE International Conference on Advanced Networks and Telecommunications Systems ANTS 2023.

7.4 Edge Learning as a Hedonic Game in LoRaWAN

Participants: Kinda Khawam *(Université de Versailles Saint-Quentin-en-Yvelines,ROCS, LISN, Université Paris Saclay)*, Samer Lahoud *(IRISA, Université de Rennes 1, France)*, Cédric Adjih, Serge Makhoul *(Saint-Joseph University of Beyrouth, Lebanon)*, Rosy Al Tawil *(Saint-Joseph University of Beyrouth, Lebanon)*, Steven Martin *(ROCS, LISN, Université Paris Saclay)*.

Federated learning provides access to more data which is paramount for constrained LoRaWAN devices with limited memory storage. Learning on a larger data set will reduce the variance of the learned model, hence reducing its error. However, federating the learning process incurs a communication cost among learning devices that must be taken into account. In this paper, we formulate a Cooperative Hedonic game and introduce a new cost function that captures both the learning error and communication cost. LoRaWAN devices engage in the devised game by identifying if they should keep their learning local or federate with other devices in order to reduce both their learning error and communication cost. We compute the optimal size of formed coalitions and assess their stability. Then, we show through extensive simulations that devices have anincentive to form learning coalitions depending on the data characteristics at hand and the communication cost of LoRaWAN.

This article was presented at the conference ICC 2023.

7.5 5G Communications [Axis 1]

7.5.1 A Novel Radio-Aware and Adaptive Numerology Configuration in V2X 5G NR Communications

Participants: Lam Thanh-Son Nguyen *(Paris Saclay University & Sorbonne University, France)*, Sondes Kallel *(University of Paris Saclay, France)*, Nadjib Aitsaadi *(UVSQ Paris-Saclay & DAVID Lab, France)*, Cédric Adjih, Ilhem Fajjari *(Orange Labs, France)*.

As the main goal of connected autonomous vehicles' communications is to improve traffic safety and save lives, any design of a resource allocation scheme must consider the stringent requirements of these applications in terms of latency and reliability. For this, 5G cellular networks suitably address these challenges. This paper proposes a new mechanism for the telco operator to adapt the physical (PHY) layer configuration for efficient radio resource management in a 5G New Radio (NR) based system. To tackle this issue, we propose to adjust the PHY layer numerology configuration by fine-tuning it with a Radio-Aware Adaptive PHY Layer Configuration (RA-APC) algorithm in order to maximize the Effectively Transmitted Packet (ETP). Extensive simulations show that our proposal RA-APC achieves strong improvements in terms of ETP, reliability and latency while considering safety and non-safety traffic scenarios.

This article was presented at ICC 2023.

7.5.2 A Novel AI Security Application Function of 5G Core Network for V2X C-ITS Facilities Layer

Participants: Hadi Yakan *(VSQ Paris-Saclay & DAVID Lab, France)*, Ilhem Fajjari *(Orange Labs, France)*, Nadjib Aitsaadi *(UVSQ Paris-Saclay & DAVID Lab, France)*, Cédric Adjih.

5G Cellular Vehicle-to-Everything (C-V2X) is expected to become the dominant technology to enable Cooperative Intelligent Transport System (C-ITS) applications. In this paper we address the problem of detecting falsified vehicle positions sent by misbehaving vehicles targeting C-ITS application servers over 5G networks. We propose a novel security system as 5G application function. It is based on machine learning and integrated with the 5G core network to monitor, detect and prevent potential misbehavior. Based on extensive network simulations utilizing 5G network emulator, our proposal achieves very good performances, accurately reported 98

This article was presented at ICC 2023.

7.5.3 Designing Medium Access Control Protocol Sequences Through Deep Reinforcement Learning

Participants: Cedric Adjih, Chung Shue Chen *(Nokia Bell Labs)*, Chetanveer Sharma Gobin *(Institut National des Sciences Appliquées (INSA) de Lyon)*, Iman Hmedoush *(Nokia Bell Labs & Standards Research; Inria Saclay)*.

Our work aims to design protocol sequences through deep reinforcement learning (DRL). Protocol sequences are periodic binary sequences that define multiple access control among users, introduced for systems considering collision channel without feedback (CCw/oFB). In this paper, we leverage the recent advancement of DRL methods to design protocol sequences with desirable new properties, namely Throughput Maximizing User- Irrepressible (TMUI) sequences. TMUI has two specific properties: (i) user-irrepressibility (UI), and (ii) maximizing the minimum individual throughput among the users. We assumed that the transmission channel is divided into time slots and the starting time of each user in joining the system is arbitrary such that there exist random relative time offsets. We use a DRL approach to find TMUI sequences. We report the obtained TMUI protocol sequences and conduct numerical studies comparing TMUI against slotted ALOHA. Simulation results also show that the new medium access control (MAC) protocol does hold the UI property and can achieve substantially higher minimum individual user throughput, under the same system parameters.

The article [15] was presented at EuCNC & 6G Summit 2023 - European Conference on Networks and Communications & 6G SummitGothenburg, SwedenJun 6, 2023.

7.6 UAV and Aerial Communications [Axis 1]

7.6.1 Veterinary Drone: Blockchain-Based System for Cattle Health Monitoring

Participants: Khouloud Hwerbi *(ENSI, Tunisia; TSP, France)*, Ichrak Amdouni *(ENSI, Tunisia)*, Anis Laouiti *(TSP, France)*, Cedric Adjih *(INRIA, France)*, Leila Saidane *(ENSI, Tunisia)*.

This work exploits the potential of two important technologies which are UAVs (Unmanned Aerial Vehicles) and blockchain in the context of Agriculture 4.0. We propose a cattle health monitoring system based on UAVs that collect health measures from IoT devices equipping the animals. The main objectives of our system are twofold. First, the consumer will be aware of the quality of his/her food. Second, the national ecosystem (e.g. agriculture ministry, trade ministry) will get useful information about the quality and the number of cattle that can be put on the market. Thus, smart cattle management strategies could be undertaken afterward. The involved entities in such a system are multiple: the farmer, the veterinaries, the Ministry of Agriculture, etc... We first start by studying the system's security by applying the FMEA risk assessment methodology. Our findings motivate us to integrate blockchain technology to manage the data collected as well as the attribution of the UAVs missions via a marketplace. Thanks to its properties, this technology ensures the transparent tracking of cattle status and fairness in the payment of the UAVs managed by private operators. Finally, we develop a proof of concept using the Sui blockchain platform.

This work was published in the conference International Wireless Communications and Mobile Computing, IWCMC 2023.

7.6.2 A Deep Learning Approach to Topology Configuration in Multi-Hop Wireless Networks with Directional Antennas: nodes2net

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

Multi-hop wireless networks can be optimized using directional antennas, particularly in scenarios like drone networks, where link performance is heavily dependent on nodes' positions. This optimization ensures high operational guarantees, instantaneous connectivity, minimum SNRs and SINRs thresholds, and improved QoS. It simplifies tasks of future network layers and allows for more relaxed routing protocols and scheduling. However, attaining optimal performance via network configuration, which involves selecting an antenna orientation for each node to create a link with another node, is challenging, especially when it is carried out online and in real-time. This task is highly combinatorial and is often treated as an Integer Programming (IP) problem. While it is suitable for static graphs or situations where real time solution computing is not needed, when dealing with dynamic networks that need frequent and important topology changes, one may need a lighter, offline solution.

To tackle this challenge, we present nodes2net, a method grounded in deep learning for configuring network topology. This approach uses nodes' positions as inputs and produces a set of links as output. We teach it to imitate ideal graphs obtained by more costly algorithms such as IP methods. By leveraging learning of patterns and theoretically driven properties, nodes2net can generate reliable network configuration solutions when dealing with new sets of node positions. It utilizes efficient neural network aggregation operators to facilitate and process information about the nodes, to finally produce the final solution as set of links. Our results demonstrate the competitive performance of this method.

This article was presented at PEMWN'2023.

7.6.3 Attentive, Permutation Invariant, One-Shot Node-conditioned Graph Generation for Wireless Networks Topology Optimization

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

It is common knowledge that using directional antennas is often mandatory for Multi-hop ad-hoc wireless networks to provide satis- fying quality of service, especially when dealing with an important num- ber of communication nodes [1]. As opposed to their omnidirectional counterpart, directional antennas allow for much more manageable in- terference patterns: a receiving antenna is not necessarily interfered by nearby emitting antennas as long as this receiving antenna is not di- rected towards these undesired emission beams. Two nodes then need to steer one of their antennas in the direction of the other node in order to create a network communication link. These two users will then be able to, in turn, emit and receive to and from each other. The scope of this work resides in finding a centralized algorithm to governate these antenna steering decisions for all users to instantaneously provide a valid set of communication links at any time given the positions of each user. The problem that raises is then a geometrical one that implies finding topologies of network links that present satisfying throughput and over- all QoS and guarantee instantaneous connectedness i.e. the computed set of links allows any user to reach any other user in a certain number of hops. Building such optimized link topologies makes further tasks, such as routing and scheduling of the network, much simpler and faster. This problem is highly combinatorial and, while it is solvable with traditional Mixed Integer Programming (MIP), it is quite challenging to carry it out in real time. For this purpose, we propose a Deep Neural Network that is trained to imitate valid, solved instances of the problem. We use the Attention mechanism to let nodes exchange information in order to capture interesting patterns and properties that then enable the neural network to generate valid network link topologies, even dealing with unseen sets of users positions

This article was presented at MLN'2023.

7.7 TinyML and Edge AI

Participants: Cédric Adjih, Nadjib Achir, Emmanuel Baccelli, Anis Laouiti *(IPP/Telecom SudParis)*, Fernando Molano, Yunmeng Shu, Pengwenlong Gu.

This year, work continued on the topic of TinyML and 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 have also worked on the compact transfer of ML models with network protocols, and the integration of TinyML in the RIOT operating system. We also co-advised and experimented with developing models on Nvidia Jetson Nano for specific applications.

Finally, a keynote was given on "From TinyML to Distributed Architectures: The Evolution of Machine Learning in IoT"' in Oct. 2023 in the IoT & ET workshop.

7.8 TinyML Evaluation Toolkit for Low-Power IoT [Axis 1]

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

Results from the TinyML community demonstrate that, it is possible to execute machine learning models directly on the terminals themselves, even if these are small microcontroller-based devices. However, to date, practitioners in the domain lack convenient all-in-one toolkits to help them evaluate the feasibility of executing arbitrary models on arbitrary low-power IoT hardware. To this effect, we present in this paper U-TOE, a universal toolkit we designed to facilitate the task of IoT designers and researchers, by combining functionalities from a low-power embedded OS, a generic model transpiler

and compiler, an integrated performance measurement module, and an open-access remote IoT testbed. We provide an open source implementation of U-TOE and we demonstrate its use to experimentally evaluate the performance of various models, on a wide variety of low-power IoT boards, based on popular microcontroller architectures. U-TOE allows easily reproducible and customizable comparative evaluation experiments on a wide variety of IoT hardware all-at-once. The availability of a toolkit such as U-TOE is desirable to accelerate research combining Artificial Intelligence and IoT towards fully exploiting the potential of edge computing.

This work was published at IEEE/IFIP PEMWN 2023 [27].

7.9 Standardization of General-Purpose Secure Software Updates for IoT Devices [Axis 1]

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-22 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 is published in the IETF Internet Draft available online at draft-ietf-suit-manifest-22.

7.10 Secure Software Updates for Low Earth Orbit CubeSat Payloads [Axis 1]

Participants: Didier Donsez, Olivier Alphand, François-Xavier Molina, Emmanuel Baccelli, Koen Zandberg
.

CubeSat design is facilitated by the increasing availability of open-source software in the domain, and a variety of low-cost hardware blueprints based on commodity microcontrollers. We attain the rock-bottom price to reach orbit as entities that design, launch and operate CubeSats started selling to multiple tenants tiny rack slots (typically 0,25U each) for low-power payloads that may be hosted on their CubeSat. The question arises of how to provide state-of-the-art security for software updates on a multi-tenant CubeSat, whereby mutual trust between tenants is limited. In this paper, we provide a case-study: ThingSat, a low-power payload we designed, is currently hosted on a CubeSat orbiting at 500km altitude operated by a separate entity. We then design Cubedate, a framework for securing continuous deployment of software to be updated on orbiting multi-tenant CubeSats. We also provide a highly portable open-source implementation of Cubedate, based on the IoT operating system RIOT, which we evaluate experimentally.

This work is published at IEEE/IFIP PEMWN 2023 [30].

7.11 Privacy-Preserving Contact Tracing with Cheap Low-power Wireless Tokens [Axis 1]

Participants: François-Xavier Molina, Vincent Roca, Roudy Dagher, Emmanuel Baccelli, Nathalie Mitton, Antoine Boutet, Matthieu Cunche.

Contact Tracing (CT) is an old, recognized epidemiological tool, and since a digital variant is now within reach, a variety of smartphone-based solutions have been rapidly developed and deployed since

2020, with mixed results and amid controversies. Yet, achieving reliable and effective digital CT at large scale is still an open problem.In this work, we contribute with an open source software platform on top of which various CT solutions can be quickly developed and tested. More specifically, we design PEPPER, which jointly leverages Bluetooth Low Energy (BLE) and Ultra Wide Band (UWB) radios for contact detection, combined with the DESIRE privacy-preserving CT protocol. We show that PEPPER+DESIRE can operate on cheap physical tokens based on low-power microcontrollers, opening new use-cases with less personal, potentially disposable devices, that could be more widely used. We also evaluate the complementarity of Bluetooth and UWB in this context, via experiments mimicking various scenarios relevant for CT. Compared to BLE-only CT, we show that UWB can decrease false negatives (e.g., in presence of human body occlusion), meaning that more actual contacts will be found, a key benefit from an epidemiological viewpoint. Our results suggest that, while PEPPER+DESIRE improves precision over state-of-the-art, further research is required to harness UWB-BLE synergy for CT in practice. To this end, our open source platform (which can run on an open-access testbed) provides a useful playground for the research community.

This work is published at IEEE WoWMoM 2023 [24].

7.12 UAV Communications [Axis 1]

7.12.1 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 work has been published in [49].

7.12.2 Blockchain adapted to IoT

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 has been presented in PEMWN 2023 [28]

7.13 Collecting datasets for mobility investigation [Axis 2]

7.13.1 Energy Efficient adaptive sampling frequency of human mobility [Axis 2]

Participants: Panagiota Katsikouli, Aline Carneiro Viana, Marco Fiore, Diego Madariaga.

In this work, we aim at answering the question *"at what frequency should one sample individual human movements so that they can be reconstructed from the collected samples with minimum loss of information?"*.

Our analyses on fine-grained GPS trajectories from users around the world unveil *(i)* seemingly universal spectral properties of human mobility, and *(ii)* a linear scaling law of the localization error with respect to the sampling interval. Our analysis of fine-grained trajectories unveils a novel linear scaling law of the localization error with respect to the sampling interval. Such results were published at IEEE Globecom 2017 [41].

Building on these results, we challenge the idea of a fixed sampling frequency and present a light-weight, energy-efficient, mobility aware adaptive location sampling mechanism. We thus present DUCTILOC, a location sampling mechanism that takes advantage of the law above to profile users and then adapt the position tracking frequency to their mobility. Our design is energy efficient, as DUCTILOC does not rely on power-hungry sensors or expensive computations; moreover, it provides a handy knob to control energy usage, by configuring the target positioning accuracy. Real-world experiments with an Android implementation of DUCTILOC show that it can effectively adjust the sampling frequency to the mobility habits of each individual and target accuracy level, reducing the energy consumption by 60% to 98% with respect to a baseline periodic sampling.

This work is published at the IEEE ACCESS journal [14].

7.13.2 Introducing benchmarks for evaluating user-privacy vulnerability in WiFi

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

WiFi-based crowdsensing is a major source of data in a variety of domains such as human-mobility, pollution-level estimation, and, opportunistic networks. MAC randomisation is a backbone for preserving user-privacy in WiFi, as devices change their identifiers (MAC addresses). MAC association frameworks in the literature are able to associate randomized MAC addresses with a device. Such frameworks facilitate the continuation and validity of works based on device-based identifiers. In this paper, we first question and verify the reliability of these frameworks with respect to the datasets (scenarios) used for their validation. Indeed, we observe a substantial discrepancy between the performances obtained by these frameworks when confronting them with different contextual environments. We identify that the device heterogeneity in the input scenario is privacy-preserving. Henceforth, we propose a novel metric: *randomization complexity*, capable of successfully catching the *degree of randomization* in evaluated datasets. Existing and new frameworks can thus be *benchmarked* using this metric to ensure their *reliability* for any datasets with similar or lower randomization complexities. Finally, we open discussions on the potential impact of the benchmarks in the domain of MAC randomization.

This article was published at IEEE VTC'23 [23] and is part of the contributions described in Abhishek's PhD thesis [32]. He did a PhD under the supervision of Aline C. Viana and Nadjib Achir. He defended in October 2023.

7.13.3 Bleach: From WiFi probe-request signatures to MAC association

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 is related to the ANR MITIK project (2020-2025). It is under-submission to a journal and is described in Abhishek's PhD thesis [32], a PhD performed under the supervision of Aline C. Viana and Nadjib Achir. He defended in October 2023.

A preliminary work discussing privacy flaws in WiFi standards was published at the IEEE LCN 2021 (Doctoral-track - Promising ideas) [45] and motivated the here above MAC association work.

7.13.4 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). It was published at WCNC 2023 [21] and is also described in Abhishek's PhD thesis [32]. He did a PhD under the supervision of Aline C. Viana and Nadjib Achir. He defended in October 2023.

7.13.5 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. To measure the severity of identified flaws by looking at the performance of current MAC association attacks, we need large-scale traces of public packets with "ground truth" information regarding randomized addresses from the same device. 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.

Once achieving effective MAC association, we reveal the inference of user locations from passively sniffed probe-requests. In this thesis, we 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 [32] was performed by Abhishek Kumar Mishra under the supervision of Aline C. Viana and Nadjib Achir and under the ANR MITIK project's funding. Abhishek defended his phd on the 19th October 2023 and is currently a Post-Doc fellow at the PRIVATICS team of INRIA Lyon.

7.14 On the Edge of the Deployment: A Conceptual and Practical Survey on Multi-Access Edge Computing Implementations [Axis 3]

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 is still on-going and our first contributions were published at the ACM Computing Surveys Journal [37]. This work is now a collaboration with University Federal de Rio de Janeiro since Pedro Cruz joined the University Federal de Rio de Janeiro as an associate professor.

7.15 Understanding the intrinsics in human mobility [Axis 2]

7.15.1 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 PhD mid-term examen and the work is still on-going.

7.15.2 SafeCityMap: From spatiotemporal mobility of our society to the COVID propagation understanding

Participants: Aline Carneiro Viana, Haron Calegari Fanteceli *(LNCC,Inria)*, Lucas Santos De Oliveira, Razvan Stanica *(Inria)*, Solohaja Rabenjamina *(Inria)*.

SafeCitymap is a data-driven project investigating how individuals' mobility patterns at a metropolitan scale were affected by the Covid-19 pandemic, and especially by the harsh French lockdown conditions enforced from March 17, 2020 to May 11, 2020 (i.e., two weeks before and during the first, second, and third lockdown). For this, we used spatiotemporal aggregated mobile phone data provided by SFR, a major SFR French telecom operator, covering a geographical region focused on the city of Paris. An

essential property of this data is its fine-grained spatial resolution, which, to the best of our knowledge, is unique in the COVID-related mobility literature.

We perform a data-driven mobility investigation and modeling to quantify (in space and time) the population attendance and visiting flows in different urban areas. Second, when looking at periods both before and during the lockdown periods, we quantify the consequences of mobility restrictions and decisions on an urban scale. For this, per zone, we define a so-called *signature*, which captures behaviors in terms of population attendance in the corresponding geographical region (i.e., their land use) and allows us automatically detect activity, residential, and outlier areas. We then study three different types of *graph centrality*, quantifying the importance of each zone in a time-dependent weighted graph according to the habits in the mobility of the population. Combining the three centrality measures, we compute per zone of the city, its *impact-factor*, and employ it to quantify the global importance of zones according to the population mobility.

Our results firstly reveal the population's daily zone preferences in terms of attendance and mobility, with a high concentration on business and touristic zones. Second, results show that the lockdown mobility restrictions significantly reduced visitation and attendance patterns on zones, mainly in central Paris, and considerably changed the mobility habits of the population. As a side effect, most zones identified as mainly having activity-related population attendance in typical periods became residential-related zones during the lockdown, turning the entire city into a residential-like area. Shorter distance displacement restrictions imposed by the lockdown increased visitation to more "local" zones, i.e., close to the population's primary residence. Decentralization was also favored by the paths preferences of the still-moving population. On the other side, "jogging activities" allowing people to be outside their residences impacted parks visitation, increasing their visitation during the lockdown. By combining the impact factor and the signatures of the zones, we notice that areas with a higher impact factor are more likely to maintain regular land use during the lockdown.

Results of such investigations are periodically posted in the interactive webpage here: SafeCityMap website. This work is published at the ACM Transactions on Spatial Algorithms and Systems [39] and a extended report is available at [38].

Currently, we are investigating if the previously described mobility modeling can be used as proxies for the inference of pollution and noise indicators in a metropolitan city. While the polution and noise depend on physical deployed sensors, mobility datasets provide more precise spatiotemporal information of larger geographical areas. Preliminary investigations show a strong correlation between such indicators and SafeCityMap mobility modeling. A new report describing such investigations is being prepared.

7.15.3 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)*.

The Federated Learning (FL) framework has been applied in multiple domains, offering solutions that provide both accuracy and data privacy protection. FL has been applied to various problems, from image classification to next word prediction. For mobility prediction specifically, some prior efforts adapted solutions from other domains to mobility problems: e.g., using image classificaiton model for transportation mode prediction by converting coordinates into pixels). Yet, directly adapting solutions from other domains can be both challenging and inefficient due to the spatial and temporal related specificities of mobility prediction. Indeed, visits to certain point of interests are directly correlated to the users' routines and preferences. These are hard to embed in models for *next word* prediction or image classification, which are more concerned with grammatical structures of a language and recognition of patterns on a static low-dimensional space.

Yet, specifically for human mobility prediction, prior solutions have neglected the impact that the naturally heterogeneous human patterns may have on FL effectiveness. Also, such prior solutions are based on the social network datasets, that are both sparse in space and coarse in time, challenging routine and mobility patterns characterization. Hence, prior evaluations of FL on mobility prediction are limited and may overestimate the robustness of the proposed solutions.

In this work, we aim to fill this gap by analyzing the performance of alternative FL-based mobility predictions in scenarios with users with varying mobility patterns, identified in real and less sparse human mobility data. We aim to answer the following question: *How do existing FL-based mobility prediction models perform for users with very different mobility patterns, such as very repetitive behavior (e.g., routines) or more exploratory visiting patterns (e.g., tourists)?* Our analyses comprise both model effectiveness (accuracy) and efficiency (resource usage and execution time), and offer insights into possible improvements to current FL solutions. Heterogeneity on the (fine-grained) spatial and temporal mobility patterns directly impact prediction, hardening the FL performance analysis.

How preliminary results show considerable impact that different mobility patterns can have on both the effectiveness and efficiency of the FL models. Easier to predict users (i.e., with a strong routini in their daily life: visite regular locations and are very often stationary) experience great improvements on the accuracy of both models, accelerated the learning process and reduced resource consumption. Contrarily, users with less routine, i.e., that are more prone to explore and discover new areas, have challenged both models on every aspect, specially accuracy. Indeed, even a small fraction of them (14%) greatly impacted FL models in some senarios, evidencing the impact that heterogeneity has on the solutions.

These initial results offer many future directions of exploration. For example, we aim to study strategies to explicitly incorporate into model training the different properties of the mobility profiles, as well as investigate the performance trade-offs of favoring one particular profile over the others. Studying how the FL solutions can adapt to fluctuations in mobility patterns (and even profiles) over time is also worth pursuing.

A preliminary version of this work was published as a poster at the NetMob 2023 conference. This work is on-going and constitutes the Master thesis of Joao Esper to be submissed on Mars 2024.

7.16 Leveraging human mobility understanding [Axis 2 and 3]

7.16.1 Data offloading decision via mobile crowdsensing [Axis 2 and 3]

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) [47]. 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 last extended work is published at the IEEE Transactions on Network and Service Management [46]. The work and the collaboraiton 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.

7.16.2 POPAyI: *Muscling* Ordinal Patterns for low-complex and usability-aware transportation mode detection [Axis 2]

Participants: Isadora Cardoso, Joao B. Borges, Aline Carneiro Viana, Antonio F. Loureiro, Heitor Ramos.

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 2% using 1000 fewer parameters than a lightweight DL approach.

This work has been just accepted to the IEEE Internet of Things Journal (notification received on 6th January 2024).

7.17 Privacy and security issues in collected wireless data [Axis 2]

When performing analytics from collected data related to smart devices, privacy issues come into play that can not be ignored. Dealing with such issues is essential to allow the leveraging of any extracted data knowledge in networking solutions. In this line of work, we investigate solutions allowing the design of privacy-compliant networking solutions that take profit from individuals' wireless data.

7.17.1 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 [9] and a technical report can be found in [42].

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 6) is mentioned in the Software section and can be found at Inria GitLab. Related publications were published at IEEE WCNC 2023 [20], at the ACM Conext Student Workshop 2022 [44], at the NetMob 2023 conference, (Book of Abstract) , and at the French Cores 2022 [35] and 2023 [19]. This latter was awarded as the best paper at Cores. An extended version is also under submission.

7.17.2 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 a journal.

7.17.3 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's PhD thesis [32] under the supervision of Aline C. Viana and Alain Tchana and under INRIA funding. Anne Josiane defended her Ph.D. on 11th May 2023 and is currently a Post-Doc fellow at TU-BErlin.

7.18 Geometric Quantum Information Theory

Participants: Philippe Jacquet, Veronique Joly.

We refer to the black hole information paradox. We look after the existence of eigenvalues with non zero imaginary part in the Gordon Klein equation with Schwartzschild metric. Such eigenvalues exist because the Schwartzschild metric is singular on the event horizon. The eigenvalues should be proportional to the inverse of black hole radius. The existence has many impacts, among other that black holes should be again eternal. However the effects of the unitary violation should not be detectable within known black holes with existing technologies.

This work has been presented in Geometric Science of Information 2023 [18].

7.19 Energy Saving in Mobile Multi-Hop Sensor Networks

Participants: Bartlomiej Blaszczyszyn, Philippe Jacquet, Bernard Mans, Dalia Popescu.

We have characterized some trade-offs between the end-to-end communication delay and the energy in urban mobile communications with infrastructure assistance. Our study exploits the self-similarity of the location of communication entities in cities by modeling them with a hyperfractal model which characterizes the distribution of mobile nodes and relay nodes by a fractal dimension d_F and d_r, both larger than the dimension of the embedded map. We compute theoretical bounds for the end-to-end communication hop count considering two different energy-minimizing goals: either total accumulated energy or maximum energy per node. Let $\delta > 1$ be the attenuation factor in the street, we prove that when we aim to a total energy cost of order $n^{(1-\delta)(1-\alpha)}$ the hop count for an end-to-end transmission is of order $n^{1-\alpha/(d_F-1)}$, with $\alpha < 1$ is a tunable parameter. This proves that for both goals the energy decreases as we allow choosing routing paths of higher length. The asymptotic limit of the energy becomes significantly small when the number of nodes becomes asymptotically large. A lower bound on the network throughput capacity with constraints on path energy is also given. We show that our model fits real deployments where open data sets are available.

This work has been published in [13].

7.20 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 been sollicited to edit a special issue in "Entropy" about this subject.

7.21 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.

7.22 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. We present the analysis of the depth-first search algorithm in a random digraph model with geometric 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. The depth-first search algorithm may be useful to model the propagation of disease or information in a dynamic graph.

This work has been presented in AofA 2022 and is published in [40].

8 Bilateral contracts and grants with industry

8.1 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.

9 Partnerships and cooperations

9.1 International initiatives

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

MLNS2

Title: Machine Learning, Network, System and Security

Duration: 2021–2023

Coordinators: David Bromberg, (French side: University of Rennes 1, Inria WIDE-IRISA) and Thomas B. Bouetou (Cameroonian side: ENSPY)

Partners:

- University of Rennes 1, France
- WIDE-IRISA, TRiBE (INRIA), France
- ENS-Lyon, France
- ENSPY (Cameroonian)

Inria contact: David Bromberg

website: MLNS2 website

Summary: The MLNS2 (Machine Learning, Network, System and Security) is an Inria International Team involving three Inria teams (AVALON, WIDE, and TRiBE), the ENS Lyon (LIP), and the Université of Yaoundé I (Cameroon). Smartphones become the most natural tool for people to communicate, and as such, it involves more than five billion people around the globe. As a consequence, cellular networks are an infrastructure of prime importance, so does the software ecosystem related to smartphones. In this context, the aim of this collaboration is to adequately design and investigate efficient approaches to fight against simbox frauds and malware proliferation. Addressing such challenges require multidisciplinary knowledge such as Machine Learning, Network, System, and Security (MLNS2). In this direction, we focus on two major challenges: Attacks at the infrastructure level and Attacks at the software ecosystem level.

MAGICO

Title: Machine-Learning Enabled Next-Generation IoT Communications

Duration: 2022–2024

Coordinator: Sanjeev Sharma (IIT BHU Varanasi) and Kuntal Deka (IIT Guwahati)

Partners:

- Indian Institute of Technology, Varanasi ITT (BHU) and Indian Institute of Technology, Guwahati (India)

Inria contact: Cédric Adjih

Website: MAGICO site

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.

9.1.2 STIC/MATH/CLIMAT AmSud projects

LINT

Participants: Aline Carneiro Viana, Nadjib Achir.

Title: Leveraging federated mobility learning for tactile Internet services

Program: STIC-AmSud

Duration: January 1, 2023 – December 31, 2024

International Coordinator: Nadjib Achir

Partners:

- Universidad del Desarrollo, Santiago de Chile, Chile
- Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil
- Universidad de Buenos Aires, Buenos Aires, Argentina
- INRIA Saclay, France
- Universidade Federal de Minas Gerais, Brazil
- Universidade Federal de Goiás, Brazil
- University Sorbonne Paris Nord, France

Inria contact: Nadjib Achir

Summary: The Tactile Internet requires ultra-low latency and high availability of cloud-like resources. Multi-Access Edge Computing (MEC) addresses this requirement, serving users with MEC hosts nearby. Nevertheless, user mobility hinders this strategy, increasing the host-user distance over time. LINT (Leveraging federated mobility learning for Tactile Internet's services) aims to predict user trajectories with federated learning, using them to optimally allocate MEC resources, while preserving user privacy. The project goals are:

- Development of theoretical foundations, analytical methods, and algorithmic tools to support privacy-conserving mobility characterization of personal devices in the Tactile Internet
- Practical experimentation of adaptative resource management strategies for latency-dependent Tactile applications in Mobile Edge Computing (MEC) infrastructure.
- Investigation of Federated Learning mechanisms for user-privacy preservation.

9.1.3 Participation in other International Programs

PHC-Utique 2021 - PARADICE (21G1116)

Title: Precision Agriculture in the Era of Drones and Artificial Intelligence

Partner Institution(s): Laboratoire CRISTAL, ENSI (Ecole Nationale des Sciences de l'Informatique), Tunisia Telecom SudParis, IPP, France Inria Saclay, France

Date/Duration: 2021-2023

Additional info: See Paradice web site. This project targets advanced technology, focusing on networked Unmanned Aerial Vehicles (UAVs) integrated with machine learning (ML) algorithms for tasks like early disease detection and resource management. Key technological aspects include the use of artificial intelligence for real-time decision-making and navigation of drones. Communication technologies, such as TinyML, embedded ML, edge ML, and various network protocols, are central to ensuring effective drone coordination and data transmission. The integration of these technologies aims to enhance agricultural efficiency and responsiveness to environmental and health challenges. Overall, the project represents a blend of cutting-edge ML and communication technologies applied in the agricultural sector.

9.2 International research visitors

9.2.1 Visits of international scientists

Other international visits to the team

- Jussara Almeida

  Status: Researcher

  Institution of origin: Federal University of Minas Gerais

  Country: Brazil

  Dates: from May 2023 until Jun 2023

  Context of the visit: Kickoff of STIC AmSud LINT and collaboration on Mobility Federated Learning

  Mobility program/type of mobility: STIC AmSud LINT

- Luis Henrique Kosmalski Costa

  Status: Researcher

  Institution of origin: Federal University of Rio de Janeiro

  Country: Brazil

  Dates: from May 2023 until Jun 2023

  Context of the visit: Kickoff of STIC AmSud LINT and collaboration on Mobility predictability

  Mobility program/type of mobility: STIC AmSud LINT

- Leo Ferres

  Status: Researcher

  Institution of origin: Universidad del Desarrollo

  Country: Chile

  Dates: from May 2023 until Jun 2023

  Context of the visit: Kickoff of STIC AmSud LINT and collaboration on Mobility Generation

  Mobility program/type of mobility: STIC AmSud LINT

- Mariano Beiró

  Status: Researcher

  Institution of origin: University of Buenos Aires

  Country: Argentina

  Dates: from May 2023 until Jun 2023 and from Nov 2023 until Nov 2023

  Context of the visit: Kickoff of STIC AmSud LINT and collaboration on Mobility generation and accessibility issues

Mobility program/type of mobility: STIC AmSud LINT

- Ichrak Amdouni

  Status: Researcher

  Institution of origin: ENSI Tunis

  Country: Tunisia

  Dates: 12 Feb. to 18 Feb. 2023 and 13 Mar. to 23 Mar. 2023

  Context of the visit: Progress on the Project "Precision Agriculture in the era of Drones and Artificial Intelligence" (PARADICE)

  Mobility program/type of mobility: PHC Utique - PARADICE (21G1116)

- Leila Azouz Saidane

  Status: Researcher

  Institution of origin: ENSI Tunis

  Country: Tunisia

  Dates: from 12 february 2023 to 18 february 2023, from 13 march 2023 to 19 march 2023, from 23 october 2023 to 28 october 2023, and from 11 december 2023 to 16 december 2023.

  Context of the visit: Progress on the Project "Precision Agriculture in the era of Drones and Artificial Intelligence" (PARADICE)

  Mobility program/type of mobility: PHC Utique - PARADICE (21G1116)

9.2.2 Visits to international teams

Research stays abroad

– Aline Carneiro Viana

  Visited University: University Federal de Rio de Janeiro

  Country: Brazil

  Dates: from December 11 until December 13, 2023

  Context of the visit: Participation in the second Workshop of STIC AmSud LINT and collaboration on Mobility generation and accessibility issues and Mobility-aware Edge resource allocations

  Mobility program/type of mobility: STIC AmSud LINT

– Anne Josiane Kouam

  Visited University: University Federal de Rio de Janeiro

  Country: Brazil

  Dates: from December 11 until December 16, 2023

  Context of the visit: Kickoff of STIC AmSud LINT and collaboration on Mobility generation and accessibility issues

  Mobility program/type of mobility: STIC AmSud LINT

– Nadjib Achir

  Visited University: University Federal de Rio de Janeiro

  Country: Brazil

  Dates: from December 11 until December 16, 2023

  Context of the visit: Participation in the second Workshop of STIC AmSud LINT and collaboration on Anomaly detection and impact of mobility on the Edge

  Mobility program/type of mobility: STIC AmSud LINT

– Cédric Adjih

Visited University: ENSI Tunis

Country: Tunisia

Dates: 16 oct to 20 oct 2023

Context of the visit: Participation in the PhC Utique PARADICE meeting, and at the the workshop IoT & ET 2023.

Mobility program/type of mobility: PHC Utique (PARADICE)

9.3 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, 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.

9.3.1 ANR

MITIK

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

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.

NF FITNESS - From IoT breakthroughs to Network Enhanced ServiceS

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

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€)

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.

NF NAI - Architectures and Infrastructures de Réseaux et Convergence réseaux, cloud and capteurs

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€)

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).

NF PERSEUS - Power-Efficient Radio interface for Sub-7GHz distributEd massive MIMO infrastructUreS

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€)

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.

NF FPNG - French Network of Test Platforms for the Next Generation of Mobile Communications

Participants: Cedric Adjih, Fernando Molina.

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€)

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.

Mob Sci-Dat Factory - Sharing of tools for processing and analysing mobility data

Participants: Aline Carneiro Viana, Nadjib Achir, Philippe Jacquet.

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€)

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

9.4 Regional initiatives

Geostatistical and Machine Learning Methods for Sustainable Deployment of Mobility on Demand (AI4IDF)

Participants: Aline Carneiro Viana, Andrea Araldo.

Funding instrument/scientific committee: DIM AI4IDF - Intelligence Artificielle centrée sur l'humain en Ile de France

Project title: Geostatistical and Machine Learning Methods for Sustainable Deployment of Mobility on Demand

Duration: 2024–2027

Coordinator: Andrea Araldo

Other partners: TPT-IPP, TRiBE INRIA, PADAM Mobility (Siemens Mobility Group - Paris)

Budget: PhD scholarship for 3 years.

Abstract: Mobility on Demand services are offered via a fleet of vehicles that adapt their route on the fly to the observed user requests. Today, the efficiency of MoD is measured by basic metrics, such as the number of passengers served or average delay. In this project, we want instead to construct MoD around accessibility, an indicator that measures how many opportunities (jobs, schools, shops, etc.) one can reach within a limited time, starting from a certain location. In the areas where Public Transport (PT) offers good accessibility, people do not "depend upon" their (polluting) car to participate in society. Accessibility is thus a necessary condition for social,economic, and environmental sustainability. Unfortunately, PT provides insufficient accessibility in the suburbs. In such areas, MoD has been shown to be more efficient than traditional PT. We aim to exploit the potential of MoD with the objective to reduce the accessibility gap between city centres and suburbs.

10 Dissemination

10.1 Promoting scientific activities

10.1.1 Scientific events: selection

Chair of conference program committees

- Nadjib Achir: TPC co-chair of the 1st 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 28th to the 30th of November, 2023.
- Cédric Adjih: co-chair of the second Workshop on IoT and Emerging Technologies IoT & ET 2023 October 18-20, 2023, Djerba, Tunisia. Also member of the Steering Committee of IFIP/IEEE PEMWN 2023.

Member of the conference program committees

- Nadjib Achir: IEEE VCC 2023, IEEE Globecom 2023, CSNet 2023, IEEE PIMRC 2023.
- Cédric Adjih: IEEE ICC 2023, IEEE VCC 2023, IEEE Globecom 2023, CSCN'2023, WINCOM'2023, CSNet'23.
- Aline C. Viana: IEEE WoWMoM 2023

Reviewer

- Nadjib Achir: IEEE VCC 2023, IEEE Globecom 2023, CSNet 2023, IEEE PIMRC 2023.
- Cédric Adjih: IFIP/IEEE PEMWN 2023, IEEE ICC 2023, IEEE VCC 2023, IEEE Globecom 2023, CSCN'2023, WINCOM'2023, CSNet'23

10.1.2 Journal

Member of the editorial boards

- Aline C. Viana:
  - (since Feb. 2018) Editorial Board member of Urban Computing Spring book series.
  - (since May 2014) Area editor of *ACM SIGCOMM Computer Communication Review* – ACM CCR.

Reviewer - reviewing activities

– Aline C. Viana: IEEE/ACM Transactions on Networking.

10.1.3 Invited talks

– Cédric Adjih gave a keynote on From TinyML to Distributed Architectures: The Evolution of Machine Learning in IoT at the second Workshop on IoT and Emerging Technologies IoT&ET, Djerba, Tunisia, Oct 2023.
– Aline C. Viana: keynote at 5th Junior Conference on Wireless and Optical Communications (JWOC 2023)
– Aline C. Viana: invited talk at the Federal University of Rio de Janeiro in the context of the STIC AmSud LINT project
– Nadjib Achir: invited talk at first MUFRAMEX workhop on "IoT platforms for indoor air quality study", University Sorbonne Paris Nord, 22 et 23 Mai 2023.
– Nadjib Achir: invited talk at the Federal University of Rio de Janeiro in the context of the STIC AmSud LINT project

10.1.4 Scientific expertise

– Aline C. Viana: EUTOPIA Science and Innovation Post-doctoral Program.

10.1.5 Research administration

– Aline C. Viana:
  * is the leader of the TRiBE Project-Team of Inria since its creation (Jul.2019);
  * is the coordinator of ANR MITIk (since 2020-2025) and PC3 Mob Sci-Data Factory (PEPR MOBIDEC, since Sep. 2023) projects;

10.2 Teaching - Supervision - Juries

10.2.1 Teaching

– Nadjib Achir is an associate professor at the Sorbonne Paris Nord University and does his full service at the university (Engineering School). He is also the head of the third year of the "Télécommunications et Réseaux" specialty, the engineering school SupGalilée.
– Engineering School: Cédric Adjih, “Internet of Things”, 12h lab sessions in 2023, ENSEA.
– Summer School class: Nadjib Achir participated in the UNINOVIS University Summer School titled "IDEAL: IoT Data and Technology Evolution for Sustainable Smart Life" held from July 3rd to July 7th, 2023. He proposed two Labs. The first lab, conducted in collaboration with Khaled Boussetta from Sorbonne Paris Nord University, focused on the process of publishing real sensor measurements to the Cloud using REST API. The second lab, in partnership with Kari Naakka from TAMK, Finland, explored the publication of heterogeneous sensor measurements to a central MQTT broker.

10.2.2 Supervision

– PhDs supervision
  * PhD in progress: Rosario Patane, “VehiCloud: How can Vehicles increase Cloud intelligence?”, since Dec. 2021. Advisors: Lila Boukhatem (Paris-Saclay), Andrea Araldo (IMT), Nadjib Achir .

    - PhD in progress: Lucas Airam Castro de Souza, “Anomaly Detection for Vehicular Networks”, since november. 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.
    - PhD in progress: Saeed Alsabbagh (UVSQ), “Security of V2X Communications in 5g networks”, since Sep. 2022. Advisors: N. Aitsaadi, C. Adjih and A. Adouane.
    - PhD in progress: 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.
    - PhD in progress: 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.
    - PhD in progress: 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.
    - PhD in progress: Haron C. Fantecele (LNN, Brazil), “Mathematical modeling and machine learning applied to human mobility prediction”, since Feb. 2020. Advisor: Aline C. Viana and Antonio Tadeu (LNCC).
    - PhD defended on the 19th october 2023: Abhishek K. Mishra, ”Revealing and exploiting privacy vulnerabilities in users’ public wireless packets”’. Advisor: Aline Carneiro Viana and Nadjib Achir.
    - PhD defended on the 11th May 2023: Anne Josiane Kouam ”Detection of bypass frauds in cellular network datasets”’. Advisor: Aline Carneiro Viana and Alain Tchana.
- 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.
    - Joao Esper (UFMG), ”Understanding Factors that Impact Human Mobility Prediction with Federated Learning”. Advisors: Aline Carneiro Viana and Jussara Almeida, from Jan 2023 until Mars 2024.
    - Yunmeng Shu (Mines Paris and Shanghai Jiao Tong University), “Federated Learning with Network and Embedded Systems Constraints”, Advisors: Cédric Adjih and Pengwenlong Gu, from May 2023 until Aug 2023.
    - Jia Cao (ENSTA and Shanghai Jiao Tong University), “Design of Random Access Protocols with Neural Networks for the Internet of Things”’, Advisors: Cédric Adjih and Pengwenlong Gu, from Jun 2023 until Aug 2023.
    - Chetanveer Gobin (INSA Lyon), “Efficient Inference and Learning for IoT”, Advisor: Cédric Adjih, from Nov 2023 until Apr 2024.
- Internship supervision
    - Sahaj Shandilya (IIT Delhi), "Attacks on Federated Learning", Advisors: Aline Carneiro Viana and Nadjib Achir, from Jun 2023 until Jul 2023.
    - Sudhanshu Raj (IIT Delhi), “Experimentation and development of ef”, Advisor: Cédric Adjih, from May 2023 until Jul 2023.
- Team members continuously encourage, teach, and mentor students:
    - to perform international short visits;
    - to engage collaborations on related thesis subject;
    - to advise master students during their thesis;
    - to review articles, when possible;
    - to the culture of open-source code, of ethical/privacy issues in data collection, and/or of standardization, according to their thesis subject;
    - to give scientific talks (e.g., project meetings, Working Groups of associated communities, team meetings, etc);

- to participate to general activities such as *Fête de la Science*, popularization committee, shadow TPCs, etc
- for the ones interested in teaching, the good pointers at campus and when to start
- to find opportunities post-thesis: CV and personal website's advising; facilitating contacts with other Institutions/Researchers; recommendation letters

10.2.3 Juries

– Mid-term PhD defense

- Nadjib Achir (reviewer): Hwerbi Khouloud, "Optimized Architectures and Algorithms for Blockchain and IoT-based Applications", IPP Telecom Paris, 12th october 2023.
- Nadjib Achir (reviewer): Saadallah Ahmed, "Quality experience guarantee for users of an immersive 3d video system", University Bourgogne Franche-Comte, 16th june 2023.
- Cédric Adjih (reviewer): Benoît-Marie Robaglia "Application de l'IA à l'accès multiple non-coordonné" IPP Telecom Paris, June and also October 2023.
- Cédric Adjih (Reviewer): Hadi Yakan, "Security of V2X Communications in 5G - 3GPP Cellular Networks", Unversité de Versailles-Saint Quentin 24 Nov. 2023.

– PhD defense

- Aline C. Viana (reviewer): Aswin Suresh, "As How Words Move Hearts: Interpretable Machine Learning Models of Bias, Engagement, and Influence in Socio-Political Systems", September 2023.
- Aline C. Viana (examiner): Ichrak Mokhtari, "Spatio-temporal analysis of dynamic phenomenon using mobile sensors: Application to pollution plumes monitoring", INSA-Lyon and AGORA/INRIA Lyon, June 2023.
- Aline C. Viana (examiner): Solohaja Rabenjamina , "Gestion de la Mobilité Urbaine et dans le Réseau Mobile à partir de Données de Téléphonie ", INSA-Lyon and AGORA/INRIA Lyon, September 2023.
- Aline C. Viana (examiner): Victor Perrier, "LEO/GEO congestion control mechanism based on the contribution of artificial intelligence", Institut Superieur de l'Aeronautique et de l'Espace (ISAE-SUPAERO), March 2023.

10.3 Popularization

10.3.1 Internal or external Inria responsibilities

– At Inria:

- Cédric Adjih is a member of the scientific commission of Inria Saclay.
- Aline C. Viana is member of the CUMI (Commission des utilisateurs des moyens informatiques, since June 2022);
- Aline C. Viana is co-founder and member of the Mentoring Commitee of Saclay (since 2019).
- Aline C. Viana reviewed a Post-Doc proposal request for the *Commission des Moyens Incitatifs de Commission des Moyens Incitatifs* of Inria Lyon;

– At the regional eco-system:

- Cédric Adjih is a member of the Hub "Digital Infrastructure and IoT" of Systematic. Cédric Adjih was a member of the Selection Committee for an Assistant Professor position at Telecom SudParis
- Aline C. Viana was member of the selection commitee for *Section CNU n° MCF-27 - Réseaux* at TOULOUSE INP-ENSEEIHT;
- Aline C. Viana was member of the *repyramidage* commitee for *Section CNU n° Prof-27* at Université Paris-Saclay;

10.3.2 Interventions

- Aline Carneiro Viana and Nadjib Achir were invited to participate in the "le Live" popularization program on the "L'esprit sorcier" channel. This program seeks to elucidate scientific inquiries with the input of experts from prominent French public research institutions. During this program, Aline Carneiro Viana and Nadjib Achir had the chance to spotlight their research works on understanding the intricacies of human mobility and its impact on network ressources, along with addressing privacy concerns in the collection of datasets from mobile devices.

11 Scientific production

11.1 Major publications

[1] L. Amichi, A. Carneiro Viana, M. Crovella and A. Loureiro. *Impacts of novelty seeking on predictability in human mobility*. Inria, 29th Dec. 2021. URL: https://hal.inria.fr/hal-03211998.

[2] L. Amichi, A. Carneiro Viana, M. Crovella and A. A. F. Loureiro. 'Understanding individuals' proclivity for novelty seeking'. In: *ACM SIGSPATIAL 2020 - 28th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems*. Seattle, Washington, United States, Nov. 2020. URL: https://hal.inria.fr/hal-02944150.

[3] L. Amichi, A. Carneiro Viana, M. Crovella and A. a. F. Loureiro. 'From movement purpose to perceptive spatial mobility prediction'. In: ACM SIGSPATIAL 2021. Beijing, China, 2nd Nov. 2021. URL: https://hal.inria.fr/hal-03444658.

[4] L. Amichi, A. C. Viana, M. Crovella and A. A. F. Loureiro. 'Explorateur ou Routinier: Quel est votre profile de mobilité?' In: ALGOTEL 2020 – 22èmes Rencontres Francophones sur les Aspects Algorithmiques des Télécommunications. Lyon, France, 28th Sept. 2020. URL: https://hal.science/hal-02868049.

[5] H. C. Fantecele, S. Rabenjamina, A. Carneiro Viana, R. Stanica and A. Ziviani. *SafeCityMap (1st phase) – COVID INRIA mission: Investigating population mobility habits in metropolitan zones and the lockdown impact using mobile phone data*. Inria, 6th May 2021. URL: https://hal.inria.fr/hal-03219274.

[6] P. Jacquet, D. Milioris and W. Szpankowski. 'Joint String Complexity for Markov Sources: Small Data Matters *'. In: *Discrete Mathematics and Theoretical Computer Science* (2020). URL: https://hal.archives-ouvertes.fr/hal-03129901.

[7] L. Jouans, A. Carneiro Viana, N. Achir and A. Fladenmuller. 'Associating the Randomized Bluetooth MAC Addresses of a Device'. In: *Consumer Communications & Networking Conference*. Las Vegas, United States, Jan. 2021. URL: https://hal.inria.fr/hal-03045555.

[8] P. Katsikouli, D. Madariaga, M. Fiore, A. Carneiro Viana and A. Tarable. *A Novel Sensor-Free Location Sampling Mechanism*. University of Copenhagen, Faculty of Science, Denmark; Inria Saclay; NIC Chile Research Labs, University of Chile; IMDEA Software Institute; CNR - IEIIT, 1st Feb. 2021. URL: https://hal.inria.fr/hal-03127182.

[9] A. J. Kouam, A. Carneiro Viana and A. Tchana. 'SIMBox bypass frauds in cellular networks: Strategies, evolution, detection, and future directions'. In: *Communications Surveys and Tutorials, IEEE Communications Society* (2021). DOI: 10.1109/COMST.2021.3100916. URL: https://hal.inria.fr/hal-03105845.

[10] M. Saito, M. Matsumoto, V. Roca and E. Baccelli. *TinyMT32 Pseudorandom Number Generator (PRNG) (RFC 8682)*. Ed. by R. E. (https://www.rfc-editor.org/). RFC 8682, Standards Track, TSVWG (Transport Area) working group of IETF (Internet Engineering Task Force), https://www.rfc-editor.org/rfc/rfc8682.html. Jan. 2020. URL: https://hal.inria.fr/hal-02449210.

[11] W. Seifeddine, C. Adjih and N. Achir. 'Dynamic Hierarchical Neural Network Offloading in IoT Edge Networks'. In: PEMWN 2021 - 10th IFIP International Conference on Performance Evaluation and Modeling in Wireless and Wired Networks. Ottawa / Virtual, Canada: IEEE, 23rd Nov. 2021, pp. 1–6. DOI: 10.23919/PEMWN53042.2021.9664700. URL: https://hal.inria.fr/hal-03533536.

[12] K. Zandberg, E. Baccelli, S. Yuan, F. Besson and J.-P. Talpin. 'Femto-Containers: Lightweight Virtualization and Fault Isolation For Small Software Functions on Low-Power IoT Microcontrollers'. In: Middleware 2022 - 23rd ACM/IFIP International Conference Middleware. quebec, Canada, 7th Nov. 2022, pp. 1–12. DOI: 10.1145/3528535.3565242. URL: https://hal.inria.fr/hal-03888109.

11.2 Publications of the year

International journals

[13] B. Blaszczyszyn, P. Jacquet, B. Mans and D. Popescu. 'Energy and Delay Trade-Offs of End-to-End Vehicular Communications using a Hyperfractal Urban Modelling'. In: *Annals of Telecommunications - annales des télécommunications*. special issue on 5+G Network Energy Consumption, Energy Efficiency and Environmental Impact (2023). DOI: 10.1007/s12243-022-00939-2. URL: https://hal.science/hal-03942997.

[14] P. Katsikouli, D. Madariaga, A. Carneiro Viana, A. Tarable and M. Fiore. 'DuctiLoc: Energy-efficient Location Sampling with Configurable Accuracy'. In: *IEEE Access* 11 (22nd Sept. 2023), pp. 15375–15389. DOI: 10.1109/ACCESS.2023.3243731. URL: https://inria.hal.science/hal-04196308.

International peer-reviewed conferences

[15] C. Adjih, C. Shue Chen, C. Gobin and I. Hmedoush. 'Designing Medium Access Control Protocol Sequences Through Deep Reinforcement Learning'. In: EuCNC & 6G Summit 2023 - European Conference on Networks and Communications & 6G Summit. Gothenburg, Sweden, 6th June 2023. URL: https://inria.hal.science/hal-04070131.

[16] J. P. Esper, N. Achir, K. V. Cardoso and J. Almeida. 'Impact of User Privacy and Mobility on Edge Offloading'. In: PIMRC 2023 - IEEE 34th Annual International Symposium on Personal, Indoor and Mobile Radio Communications. Toronto, France: IEEE, 5th Sept. 2023, pp. 1–6. DOI: 10.1109/PIMRC56721.2023.10293816. URL: https://hal.science/hal-04393555.

[17] I. Hmedoush, P. Gu, C. Adjih, P. Mühlethaler and A. Serhrouchni. 'DS-IRSA: A Deep Reinforcement Learning and Sensing Based IRSA'. In: GLOBECOM 2023 - IEEE Global Communications Conference. Kuala Lumpur, Malaysia, 4th Dec. 2023. URL: https://inria.hal.science/hal-04238023.

[18] P. Jacquet and V. Joly. 'Unitarity excess in Schwartzschild metric'. In: *Lecture Notes in Computer Science 14072*. GSI 2023 - 6th International Conference on Geometric Science of Information. Vol. LNCS-14072. Geometric Science Of Information. Saint Malo, France, 30th Aug. 2023. URL: https://hal.science/hal-04395188.

[19] A. J. Kouam, A. Carneiro Viana, P. Martins, C. Adjih and A. Tchana. 'Signalisation cellulaire pour la detection des fraudes de contournement'. In: CoRes 2023 - 8èmes Rencontres Francophones sur la Conception de protocoles, l'évaluation de performances et l'expérimentation de Réseaux de communication. Cargèse (Corse), France, May 2023. URL: https://hal.science/hal-04087350.

[20] A. J. Kouam, A. Carneiro Viana and A. Tchana. 'LSTM-based generation of cellular network traffic'. In: WCNC 2023 - IEEE Wireless Communications and Networking Conference. Glasgow, United Kingdom, 26th Mar. 2023. URL: https://inria.hal.science/hal-03897099.

[21] A. Kumar Mishra, A. Carneiro Viana and N. Achir. 'Do WiFi Probe-Requests Reveal Your Trajectory?' In: WCNC 2023 - IEEE Wireless Communications and Networking Conference. Glasgow, United Kingdom, 26th Mar. 2023. URL: https://inria.hal.science/hal-03906579.

[22] F. Marcoccia, C. Adjih and P. Mühlethaler. 'A Deep Learning Approach to Topology Configuration in Multi-Hop Wireless Networks with Directional Antennas: nodes2net'. In: PEMWN 2023 - The 12th IFIP/IEEE International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks. Berlin, Germany, 27th Sept. 2023. URL: https://hal.science/hal-04387755.

[23] A. K. Mishra, A. Carneiro Viana and N. Achir. 'Introducing benchmarks for evaluating user-privacy vulnerability in WiFi'. In: VTC2023-Spring - The IEEE 97th Vehicular Technology Conference. Florence, Italy, 20th June 2023. URL: https://hal.science/hal-04171864.

[24] F.-X. Molina, V. Roca, R. Dagher, E. Baccelli, N. Mitton, A. Boutet and M. Cunche. 'PEPPER: Precise Privacy-Preserving Contact Tracing with Cheap, BLE/UWB Capable Tokens'. In: WoWMoM 2023 - 24th IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks. Boston, United States: IEEE, 12th June 2023, pp. 1–10. URL: https://inria.hal.science/hal-04064415.

[25] P. Mühlethaler and N. Achir. 'Analyzing and Optimizing Extended-CAM Service Using Simple Stochastic Geometry Model'. In: PEMWN 2023 - 12th IFIP/IEEE International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks. Berlin, Germany: IEEE, 27th Sept. 2023, pp. 1–6. DOI: 10.23919/PEMWN58813.2023.10304925. URL: https://hal.science/hal-04393587.

[26] R. Patanè, N. Achir, A. Araldo and L. Boukhatem. 'Can vehicular cloud replace edge computing?' In: WCNC 2024 - IEEE Wireless Communications and Networking Conference. Dubai, United Arab Emirates, 21st Apr. 2024. URL: https://hal.science/hal-04393593.

Conferences without proceedings

[27] Z. Huang, K. Zandberg, K. Schleiser and E. Baccelli. 'U-TOE: Universal TinyML On-Board Evaluation Toolkit for Low-Power IoT'. In: PEMWN 2023 - 12th IFIP/IEEE International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks. Berlin, Germany: IEEE, 27th Sept. 2023, pp. 1–6. DOI: 10.23919/PEMWN58813.2023.10304946. URL: https://hal.science/hal-04382496.

[28] P. Jacquet. 'Blockchain adapted to IoT via green mining and fractal Proof of Work'. In: PEMWN 2023 - The 12th IFIP/IEEE International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks. Berlin, Germany, 27th Sept. 2023. URL: https://hal.science/hal-04395695.

[29] F. Marcoccia, C. Adjih and P. Mühlethaler. 'Attentive, Permutation Invariant, One-Shot Node-conditioned Graph Generation for Wireless Networks Topology Optimization'. In: MLN 2023 - 6th International Conference on Machine Learning for Networking. Paris, France, 28th Nov. 2023. URL: https://hal.science/hal-04403078.

[30] F.-X. Molina, E. Baccelli, K. Zandberg, D. Donsez and O. Alphand. 'Cubedate: Securing Software Updates in Orbit for Low-Power Payloads Hosted on CubeSats'. In: PEMWN 2023 - The 12th IFIP/IEEE International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks. Berlin, France: IEEE, 27th Sept. 2023, pp. 1–6. DOI: 10.23919/PEMWN58813.2023.10304910. URL: https://hal.science/hal-04382485.

Doctoral dissertations and habilitation theses

[31] A. J. Kouam. 'Bypass frauds in cellular networks: Understanding and Mitigation'. Ecole Polytechnique (Palaiseau, France), 11th May 2023. URL: https://hal.science/tel-04402681.

[32] A. K. Mishra. 'Revealing and exploiting privacy vulnerabilities in users' public wireless packets'. Institut Polytechnique de Paris, 19th Oct. 2023. URL: https://theses.hal.science/tel-04311364.

Reports & preprints

[33] J. P. Esper, N. Achir, K. V. Cardoso and J. Almeida. *Technical report: Impact of User Privacy and Mobility on Edge Offloading*. 2023. DOI: 10.48550/ARXIV.2306.15740. URL: https://hal.science/hal-04393564.

[34] A. J. Kouam, A. Carneiro Viana and A. Tchana. *Zen: LSTM-based generation of individual spatiotemporal cellular traffic with interactions*. 2nd Jan. 2023. URL: https://inria.hal.science/hal-03910141.

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[35] A. J. Kouam, A. Carneiro Viana, A. Garivier and A. Tchana. 'Génération de traces cellulaires réalistes'. In: CORES 2022 - 7ème Rencontres Francophones sur la Conception de Protocoles, l'Évaluation de Performance et l'Expérimentation des Réseaux de Communication. Saint-Rémy-Lès-Chevreuse, France, 30th May 2022. URL: https://hal.archives-ouvertes.fr/hal-03658019.

[36] 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.

[37] 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.

[38] H. C. Fantecele, S. Rabenjamina, A. Carneiro Viana, R. Stanica and A. Ziviani. *SafeCityMap (1st phase) – COVID INRIA mission: Investigating population mobility habits in metropolitan zones and the lockdown impact using mobile phone data*. Research Report. Inria, May 2021. URL: https://hal.inria.fr/hal-03219274.

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[40] P. Jacquet and S. Janson. 'Variations on depth-first search performance in random digraphs'. In: *AofA 2022 - 33rd International Conference on Probabilistic, Combinatorial, and Asymptotic Methods in the Analysis of Algorithms*. Vol. Special Issue: Probabilistic, Combinatorial and Asymptotic Methods for the Analysis of Algorithms". Philadelphia, PA, United States, June 2022. URL: https://hal.science/hal-03537124.

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