RESEARCH CENTRE

Saclay - Île-de-France

2021 ACTIVITY REPORT

Project-Team TRIBE

inTeRnet BEyond the usual

DOMAIN

Networks, Systems and Services, Distributed Computing

THEME

Networks and Telecommunications

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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 aims 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 from 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' advents:** we focus on the learning of the behaviors of high-end IoT devices, the smartdevices. 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 in 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, smart-phones, 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 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 a 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 to deal 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 merged 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 dictating 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 aims at dealing with such requirements and challenges brought to the Intenet's edge. One should design adapted algorithms and communication mechanisms and network users' behaviors 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 structure dictating human behavior (e.g., interactions, mobility, interest, cultural patterns) are now directly influencing the way individuals interact with the 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 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.
- **Tactile Internet:** considered as 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 interaction in industrial, societal and business use cases. Application exemples are: Automation and robotics, education and training, 3D and educational games, x-reality applications and services. Our solutions aim 1) to bring intelligence and adaptivity (to individuals behaviors, IoT limitations, and context of services and environment) to 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.
- **Urban planning and disaster management applications:** Two are the team 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 during disaster situations. As a final applicability, our results are a valid indication of activity loss, and consequently, of the imposed socio-economic impact activity-labeled areas suffered during the lockdown.
- Other applications 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 (although 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.

As examples, 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.

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) will provide distributed autonomy, replacing the classical centralized structures. TRiBE results will thus contribute to (1) 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 contributors 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 the IoT devices and at the edge, we avoid inefficiencies in transmitting information back and forth.

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 sensor field's digital twin 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 [33] and Ariadne Covid Inria-Covid projects carried by members of the team reinforce such assertion.

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.

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 Highlights of the year

- The Inria White Book on Societal Challenges & Scientific Research Fields for IoT, written and coordinated by Emmanuel Baccelli in collaboration with 30+ researchers, was published in December 2021.

6.1 Awards

- In 2021, Aline Viana was awarded the medal of honor of Federal University of Goias (Goiania, Brazil), awarded for important contributions to society by former students.

7 New software and platforms

The TRiBE team actively works on the below software and platforms.

7.1 New software

7.1.1 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

Contact: Cédric Adjih

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

7.1.2 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

7.1.3 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

Publication: hal-03125920

Contact: Abhishek Mishra

Participants: Abhishek Mishra, Aline Carneiro Viana, Nadjib Achir

7.1.4 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

7.1.5 SIMBox Fraud Simulator

Name: SIMBox fraud strategies and detection simulator

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

Functional Description: SIMBoxFraudSimulator is an open-source simulator of SIMBox fraud strategies and detection methods in LTE networks. It is based on the well-known and broadly used LTE-SIM tool from 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. The aim is to deploy existing detection methods of the literature for extensive evaluations to highlight their limitations and allow to propose more accurate and rapid-evolving detection approaches.

Release Contributions: Deployment and configuration of 02 of the 03 most popular SIMBox architectures

URL: https://gitlab.inria.fr/akouamdj/simboxfraud_detection

Contact: Anne Josiane Kouam Djuigne

Partner: ENS Lyon

7.2 New platforms

Open Experimental IoT Platforms

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

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.

8 New results

8.1 Femto-Containers Architecture for DevOps on Low-Power Devices in the Internet of Things [Axis 1]

Participants: Koen Zandberg, Emmanuel Baccelli.

Development, deployment and maintenance of networked software has been revolutionized by DevOps, which have become essential to boost system software quality and to enable agile evolution. Meanwhile the Internet of Things (IoT) connects more and more devices which are not covered by DevOps tools: low-power, microcontroller-based devices. In this paper, we contribute to bridge this gap by designing Femto-Containers, a new architecture which enables containerization, virtualization and secure deployment of software modules embedded on microcontrollers over low-power networks. As proof-of-concept, we implemented and evaluated Femto-Containers on popular microcontroller architectures (Arm Cortex-M, ESP32 and RISC-V), using eBPF virtualization, and RIOT, a common operating system in this space. We show that Femto-Containers can virtualize and isolate multiple software modules, executed concurrently, with very small memory footprint overhead (below 10%) and very small startup time (tens of microseconds) compared to native code execution. We show that Femto-Containers can satisfy the constraints of both low-level debug logic inserted in a hot code path, and high-level business logic coded in a variety of common programming languages. Compared to prior work,

Femto-Containers thus offer an attractive trade-off in terms of memory footprint, energy consumption, agility and security.

This paper is under submission at ACM IPSN, and available as report [39].

8.2 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-16 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-16.

8.3 Interactive Garment: IoT-enabled Textile & Machine Learning to Direct Musical Performance [Axis 1]

Participants: Berit Greinke, Felix Biessmann, Emmanuel Baccelli.

In this work we bring together orchestra conducting, e-textile material studies, costume tailoring, low power computing and machine learning (ML). We describe a wearable interactive system comprising of textile sensors embedded into a suit, low-power transmission and gesture recognition using creative computing tools. We introduce first observations made during the semi-participatory approach, which placed the conductor's movements and personal performative expressiveness at the center for technical and conceptual development. The project is a two-month collaboration between the Verworner-Krause Kammerorchester (VKKO), technical and design researchers, currently still running. Preliminary analyses of the data recorded while the conductor is wearing the prototype demonstrate that the developed system can be used to robustly decode a large number of conducting and performative movements. In particular the user interface of the ML system is designed such that the training of the algorithms can be intuitively controlled by the conductor, in sync with the MIDI clock.

This experimental work was published in ACM TEI as a short paper in [14].

8.4 Experimental Platform for Ranging, Proximity and Contact Event Tracking [Axis 1 and 3]

Participants: Roudy Dagher, Emmanuel Baccelli, Francois-Xavier Molina, Nathalie Mitton, Alexandre Abadie.

The need for cheaper and more precise localisation techniques has recently amplified. The initial approach has been to roll out high-level software running on smartphones and leveraging Bluetooth proximity sensing. However this approach lacks both precision in terms of ranging, and flexibility in terms of experimental framework to fully explore alternative schemes for contact event tracing. In this context, we thus provide open-access nodes in an open-access experimental platform for ranging and proximity tracking, letting researchers tinker freely with the full software stack on a swarm of multi-radio, low-power devices based on cheap microcontrollers. We provide a tutorial on how to use the

platform and open source code building blocks to to program the devices, bare-metal. We then report on initial measurements we have performed using the platform. Perspectives with our platform include applicability studies and comparative evaluation for a large variety of localisation schemes combining the use of Ultra-Wide Band and Bluetooth Low-Energy for better precision and smaller energy budgets - and the use of complementary mechanism guaranteeing privacy protection, able to run directly on-board cheap IoT microcontrollers.

This work was published in IEEE INFOCOM Workshop on Computer and Networking Experimental Research using Testbeds (CNERT 2021), see [12].

8.5 Quantum-Resistant Security for Software Updates on Low-power Networked Embedded Devices [Axis 1]

Participants: Koen Zandberg, Emmanuel Baccelli, Gustavo Banegas, Benjamin Smith, Adrian Herrmann.

As the Internet of Things (IoT) rolls out today to devices whose lifetime may well exceed a decade, conservative threat models should consider adversaries with access to quantum computing power. The IETF-specid SUIT standard defines a security architecture for IoT software updates, standardizing metadata and cryptographic tools digital signatures and hash functions to guarantee the update legitimacy. SUIT performance has been evaluated in the pre-quantum context, but not yet in a post-quantum context. Taking the open-source implementation of SUIT available in RIOT as a case study, we survey post-quantum considerations, and quantum-resistant digital signatures in particular, focusing on low-power, microcontroller-based IoT devices with stringent memory, CPU, and energy consumption constraints. We benchmark a range of pre- and post-quantum signature schemes on a range of IoT hardware including ARM Cortex-M, RISC-V, and Espressif (ESP32), which form the bulk of modern 32-bit microcontroller architectures. Interpreting our benchmarks in the context of SUIT, we estimate the real-world impact of transition from pre- to post-quantum signatures.

This work is under submission at ACNS and is published as preprint in [30].

8.6 Modern Protocols: Information Centric Networking and Network Coding [Axis 3]

Participants: Hirah Malik, Cédric Adjih, Michel Kieffer *(U. Paris-Saclay, L2S, CNRS)*, Claudio Weidmann *(ENSEA)*.

Motivated by research and standardization (e.g. at the IRTF), in this line of work, we are studying two modern protocols in combination: Information Centric Networking and Network Coding. This year, we finished the definition of our protocol MICN (MILIC-ICN), a highly efficient ICN and Network Coding protocol (section 8.6.1); this protocol is based on a mathematical construction on sets, denoted MILIC (Multiple Interests for Linearly Independent Contents). MILIC is a family of solutions to the mathematical problem of "Sets Ensuring Linearly Independent Transversals" (SELIT). Machine Learning has also been applied to MICN, see Section 8.8.

8.6.1 MICN: a Network Coding Protocol for ICN with Multiple Distinct Interests per Generation

In Information-Centric Networking (ICN), consumers send interest packets to the network and receive data packets as a response to their request without taking care of the producers, which have provided the content, contrary to conventional IP networks. ICN supports the use of multiple paths; however, with multiple consumers and producers, coordination among the nodes is required to efficiently use the network resources. Network coding (NC) is a promising tool to address this issue. The challenge in the case of NC is to be able to get independent coded content in response to multiple parallel interests by one or several consumers. In this work, we propose a novel construction called MILIC (Multiple Interests

for Linearly Independent Contents) that impose constraints on how the replies to interests are coded, intending to get linearly independent contents in response to multiple interests. Several protocol variants, called MICN (MILIC-ICN), built on top of NDN (Named Data Networking), are proposed to integrate these interest constraints and NC of data packets. Numerical analysis and simulations illustrate that the MILIC construction performs well and that the MICN protocols are close to optimal throughput in some scenarios. MICN protocols compare favorably to existing protocols and show significant benefits when considering the total number of transmitted packets in the network, and in the case of high link loss rate

This paper was published in Computer Networks [5].

8.6.2 MICN: Improving Forwarding Techniques

In [5], we presented the novel protocol MICN that integrates network coding and NDN. It enables NDN to take advantage of network coding and allows fast retrieval of content. MICN enables NDN to overcome the challenges of network coding integration by proposing an Interest naming scheme ensuring retrieval of linearly independent content with each Interest.

In follow-up work, alternative approaches to reduce the number of these lingering Interests and consequently the redundant traffic. The alternative approaches are modified Interest forwarding strategies implemented at the clients or the intermediate nodes in the network. These solutions rely on heuristics. A detailed mechanism and forwarding algorithm for each modified forwarding strategy is studied, and the obtained results are compared to the classical MICN (without IC).

The ideas and the results are presented in the Ph.D. Thesis of Hirah Malik "Efficient Network Coding Protocols for Information-Centric Networks", who defended in Nov. 2021.

8.7 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)*, Charles Dumas *(Nokia Bell Labs)*, Lou Salaun *(Nokia Bell Labs)*, Kinda Khawam *(UVSQ)*.

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.

This year, we had studied two aspects or variants of IRSA: first, we revisited the variant with multiple packet reception (MPR); then we considered that the IRSA random access, as other, can be formalized as competition and can be analyzed from Game Theory point of view; finally, we applied machine-learning techniques to IRSA (in Section 8.8).

8.7.1 Design of Coded Slotted ALOHA with Interference Cancellation Errors

Participants: Iman Hmedoush, Cédric Adjih, Paul Mühlethaler *(Inria, EVA)*, Chung Shue Chen *(Nokia Bell Labs)*, Charles Dumas *(Nokia Bell Labs)*, Lou Salaun *(Nokia Bell Labs)*.

In this work, we explored a more complex variant than IRSA, Coded Slotted ALOHA (CSA).

Coded Slotted ALOHA (CSA) is a random access scheme based on the application of packet erasure correcting codes to transmitted packets and the use of successive interference cancellation at the receiver. CSA has been widely studied, and a common assumption is that interference cancellation can always be applied perfectly. In this paper, we study the design of the CSA protocol, accounting for a non-zero probability of error due to imperfect interference cancellation (IC). A classical method to evaluate the performance of such protocols is density evolution, originating from coding theory, and that we adapt to our assumptions. Analyzing the convergence of density evolution in asymptotic conditions, we derive the optimal parameters of CSA, i.e., the set of code selection probabilities of users that maximizes the channel load. A new parameter is introduced to model the packet loss rate of the system, which is non-zero due to potential IC errors. Multi-packet reception (MPR) and the performance of 2-MPR are also studied. We investigate the trade-off between optimal load and packet loss rate, which sheds light on new optimal distributions that outperform known ones. Finally, we show that our asymptotic analytical results are consistent with simulations obtained on a finite number of slots.

This work was published in the journal IEEE TVT [1].

8.7.2 A Game Theoretic Approach to Irregular Repetition Slotted Aloha

Participants: Iman Hmedoush, Cédric Adjih, Paul Mühlethaler, Kinda Khawam *(UVSQ)*.

IoT networks largely rely on distributed access of billions of devices but are still lagging in terms of combined reliability and low latency. To mend that shortcoming, it is paramount to adapt existing random access methods for the IoT setting. In this line of work, we shed light on one of the modern candidates for random access protocols fitted for IoT: the “Irregular Repetition Slotted ALOHA” (IRSA). As self-managing solutions are needed to overcome the challenges of IoT, we study the IRSA random access scheme in a distributed setting where groups of users, with fixed traffic loads, are competing for ALOHA-type channel access. To that aim, we adopt a distributed game-theoretic approach where two classes of IoT devices learn autonomously their optimal IRSA protocol parameters to optimize selfishly their own effective throughput. Through extensive simulations, we assess the notable efficiency of the game-based distributed approach. We also show that our IRSA game attains the Nash equilibrium (NE) via the ”better reply” strategy, and we quantify the price of anarchy in comparison with a centralized approach. Our results imply that user competition does not fundamentally impact the performance of the IRSA protocol.

This work was published in the journal IEEE Access [3].

8.8 Machine Learning for Network Protocols

Participants: Ibrahim Ayoub, Iman Hmedoush, Hirah Malik, Cédric Adjih, Paul Mühlethaler, Kinda Khawam *(UVSQ)*, Samer Lahoud *(ESIB)*, Chung Shue Chen *(Nokia Bell Labs)*, Michel Kieffer *(U. Paris-Saclay, L2S, CNRS)*, Claudio Weidmann *(ENSEA)*.

We have successfully applied Machine Learning methods (mostly Reinforcement Learning) to the protocols described in Section 8.6 and Section 8.7.2. Some new results are reported here.

8.8.1 Deep-IRSA: A Deep Reinforcement Learning Approach to Irregular Repetition Slotted ALOHA

Participants: Ibrahim Ayoub, Iman Hmedoush, Cédric Adjih, Kinda Khawam *(UVSQ)*, Samer Lahoud *(ESIB)*.

Irregular Repetition Slotted Aloha (IRSA) is a Random Access (RA) protocol that meets requirements for IoT networks in terms of efficiency. In this line of work, we study IRSA and introduce a variant of the

protocol which allows collided users to perform a limited number of re-transmissions. Users can also be divided into classes of service which allows prioritizing a class of users. Using simulations and Deep Reinforcement Learning (DRL), we optimize the protocol and its parameters and thus propose Deep-IRSA. We can observe the learned degree distribution and the performance for various network scenarios and parameters. The observed performance in terms of throughput is excellent. Another important outcome is that the proposed method is generic and can be applied to many variants of IRSA. In addition, our method is a very good alternative to known approaches (such as density evolution) for smaller frame sizes and more complex variants.

This work was presented at PEMWN 2021 [11].

8.8.2 Reinforcement Learning for MICN

Participants: Hirah Malik, Cédric Adjih, Michel Kieffer *(U. Paris-Saclay, L2S, CNRS)*, Claudio Weidmann *(ENSEA)*.

The heuristic-based forwarding strategies that improve network resources utilization in MICN face some shortcomings. For example, the parameters are hardcoded and require tuning for changes in the network state, e.g., in the presence of losses. Our aim in this work is to explore adaptive forwarding solutions based on reinforcement learning algorithms.

After some experimentation with Q-Learning, we adopted Policy Gradient methods. We first implemented the REINFORCE algorithm with and without the baseline, which also correspond to a *Contextual Gradient Bandit*. We further explored Deep Reinforcement Learning (DRL) approaches, and more specifically, we used The Proximal Policy Optimization algorithm (PPO).

The results indicate that RL algorithms can provide good solutions to implement an adaptive forwarding strategy. Compared to REINFORCE, DRL (PPO) can use a large set of observations and tends to converge faster toward the optimum behavior. The stochastic policy ensures that the main goals of MICN are achieved while reducing the side effect of redundant traffic observed with MICN and other NC algorithms. These results provide a good base for further exploring the integration of RL techniques in MICN to improve its performance.

The ideas and the results are presented the in the PhD Thesis of Hirah Malik "Efficient Network Coding Protocols for Information-Centric Networks", who defended in Nov. 2021.

8.9 Edge AI: Hierarchical Neural Network Offloading in IoT Edge Networks [Axis 3]

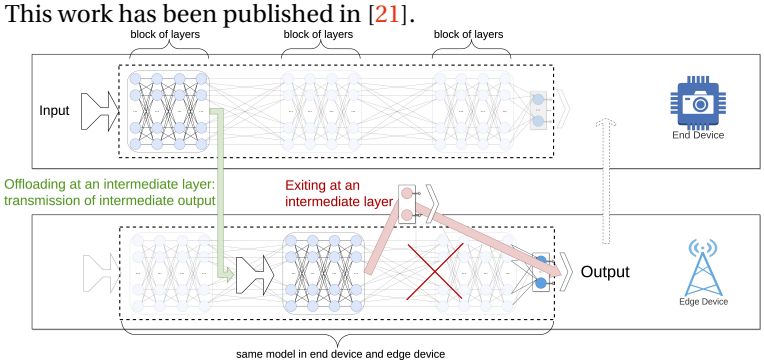
Participants: Wassim Seifeddine, Cédric Adjih, Nadjib Achir.

In recent developments in machine learning, a trend has emerged where larger models achieve better performance. At the same time, deploying these models in real-life scenarios is difficult due to the parallel trend of pushing them on end-users or IoT devices with strong resource limitations.

This year, with an internship student (Wassim Seifeddine), we developed a novel technique for embedded IoT systems that uses support from edge or cloud servers, and we propose a hierarchical execution model as shown in the following figure. Our approach combines three main ideas: first, this idea of splitting the same neural network model across two or more devices according to their computational abilities; second, the idea of *early exit* [51], where execution of the model can be stopped at some intermediate layers, trading accuracy for computational cost; and third, the idea of *offloading*, where, after a few intermediate layers, the computation can be continued from the device to the edge server. The cornerstone of our technique is a method to decide which action should be taken at every possible exit of the intermediate layers: *stay* (on device), *offload, exit.* To do so, we formulate this decision problem as a *Markov Decision Process*, and our method uses a reinforcement learning approach; precisely, we use deep reinforcement learning, where we train a smaller model, outputting a decision based on the output of the previously executed layers. Our method is capable of preserving the accuracy of the model while respecting the device's computational capabilities. It can also trade accuracy for matching various

constraints in terms of energy cost, latency, etc. We validated our approach on a modified version of the VGG Network [50] trained on the CIFAR10 dataset [44], and observed excellent results.

This work has been published in [21].



8.10 Online Drone-based Data Gathering Strategies for Ground Sensor Networks [Axis 1 and 2]

Participants: Celia Yasmine Tazibt *(University Sorbonne Paris Nord)*, Nadjib Achir.

This work presents two dynamic strategies for data gathering from a ground wireless sensor network. Compared to previous studies that aim to reduce the mobile sink's path or even on obstacle avoidance, we propose to focus on the amount of gathered data and their validity. The first strategy, named Data-driven Gathering Strategy – DDG, aims to collect the maximum amount of data stored by the sensors. We have proposed a cost function that assigns a score to each sensor node based on the amount of data each sensor node buffer carries and the distance separating that node from the drone. We have also proposed a second strategy, named Time-driven Data Gathering Strategy – TDG, which aims to collect data before a given deadline as much as possible. We also defined a cost function based on two parameters: the age of data and the distance separating the sensor node and the drone.

To evaluate the performance of our two approaches, we implemented both DDG and TDG on the OMNeT++ simulator. Furthermore, we compared our results to other existing approaches. The results show that DDG allows the drone to follow a collection path that maximizes the amount of data collected regardless of their deadline. On the other hand, the TDG strategy maximizes the amount of data collected while respecting their deadlines.

This work has been published in [7].

8.11 Smartdevices' mobility studies and leveraging [Axis 2 and 3]

The pervasiveness of high-end IoT devices associated to the fact that our lives have become dependent on connectivity and easy information access brought new possibilities to networking design practices. 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.* This line of research focus on the 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.

8.11.1 Increasing vehicles perception using cooperative relaying and priority-based beaconing [Axis 2]

Participants: Faiz Sanaullah *(University Sorbonne Paris Nord)*, Nadjib Achir, Khaled Boussetta *(University Sorbonne Paris Nord)*.

The use of vehicle onboard sensors in increasing the perception of cooperative vehicles is becoming prevailing and essential for road safety. However, trusting only on the onboard sensors could limit

the perception of the cooperative vehicles; for example, an object/vehicle can not be detected if some obstruction impedes it. The perception efficiency of vehicles can be increased beyond their field of view (FoV) by exchanging sensor-detected information through V2X communication. The perception of cars can be more accurate as frequently they share the information. However, transmitting numerous messages could saturate the communication channel and deteriorate the perception improvement, especially in dense circumstances.

In this contribution, we address both these issues and propose two different schemes, (i) an information propagating mechanism to increase the cooperative vehicle's perception above their FoV and (ii) an optimal dynamic cooperative priority-based beaconing model to coup with the channel congestion. Using the information propagation mechanism, we can increase the perception of cooperative vehicles up to their maximum communication range. On the other end, the probability-based dynamic cooperative priority beaconing scheme selects the most suitable cooperative vehicle to transmit based on its onboard sensor facility. These proposed mechanisms highly decrease the channel's contention while extending the perception beyond the FoV. We evaluate both the mechanisms for the performance in terms of vehicles awareness, channel load, and communication range through simulations for several vehicle densities. The obtained simulation results show that these proposals provide better performance compared to the classical beaconing schemes as well as eCAM.

This work has been published in [13].

8.11.2 Revealing user-mobility bounds from WiFi probe requests

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 proposal, we show, for the first time in literature, that using a theoretical error-formulation applied over real-world experimental datasets, the measurement-induced errors can be estimated as a distribution over short periods and used as *allies* to estimate trajectories bounds with high confidence as we can see in the following figure. We filter and process RSSI of sniffed WiFi probe request packets, formalize an optimization error estimation problem and finally solve it using multilateration over various samples from the estimated error distribution to obtain human-mobility bounds. In a series of simulations and analyses, we show that the proposed bounds are realistic and accurate. Furthermore, we demonstrate the accuracy and the variation of bounds according to sniffer and user-device densities wireless channel conditions.

This work is related to ANR MITIK project (2020-). We are currently finalizing a paper that should be submitted in the next few weeks.

8.11.3 How mobile can a Mobile Edge Computing be?

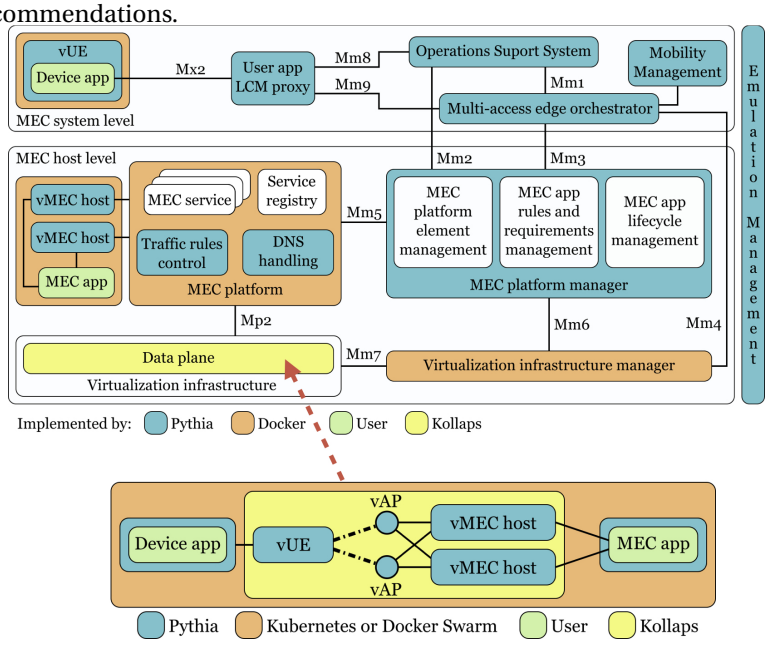
Participants: Pedro Cruz Caminha, Aline Carneiro Viana, Nadjib Achir.

The most relevant aspect of Multi-Access Edge Computing (MEC) is to provide computing resources close to the User Equipment (UE). An allocation strategy is then required to define which MEC host should serve each application running in the UEs. However, one of the direct consequences of allocating resources at the Edge is their exposure and sensitivity to the future locations due to the mobility of the UEs, which leads to non-optimal usage in the long run. It is, therefore, essential to integrate mobility

anticipation into the allocation strategy. Indeed, in a scenario with high user mobility, the distance (in terms of delay) between a given UE and each MEC host is dynamic, creating a risk to MEC's primary aspect, which is to fulfill the application's computation requirements while guaranteeing its QoS constraints. It is then essential to develop mobility-aware allocation strategies to mitigate this problem and anticipate user demands.

This issue is amplified by the lack of tools available to emulate MEC systems and evaluate the mobility impact and possible mitigation strategies. To tackle this issue, we start an intensive state of the art on the existing platforms tools, we prepared and submitted in 2021 a survey on current MEC platform implementations initiatives. We survey these practical initiatives according to their development strategies, including the ETSI MEC standard compliance, limitations, and impact. We also survey the existing tools making MEC systems a reality. Finally, we give hints to MEC issues yet to be addressed in practice. This work will help researchers and developers design their own MEC systems or improve and simplify the usability of existing ones. We are currently working on the article's revised version, which we will resubmit soon.

We then propose **Pythia** (see figure below), a MEC system emulator that receives (i) users' mobility information (UE mobility traces), (ii) MEC infrastructure specifications, (iii) a pair containing a MEC and a UE application, and (iv) an allocation strategy, outputting important metrics of user experience. In such a way, Pythia extracts and models properties of short-term mobility behavior of users to anticipate future locations in users' mobility. Such information is then leveraged at the MEC allocation of resources. Pythia emulates the network from the point-of-view of the links between the MEC hosts and the UEs while executing the MEC and UE applications in a virtual environment. We also started implementing the v0 version of the experimentation platform on Grid'5000. The adopted approach follows the ETSI recommendations.



8.11.4 Energy Efficient adaptive sampling frequency of human mobility

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

In recent years, mobile device tracking technologies based on various positioning systems have made location data collection a ubiquitous practice. Applications running on smartphones record location samples at different frequencies for varied purposes. The frequency at which location samples are recorded is usually pre-defined and fixed but can differ across applications; this naturally results in big location datasets of various resolutions. Moreover, continuous recording of locations usually results in

redundant information, as humans tend to spend a significant amount of their time either static or in routine trips, and drains the battery of the recording device.

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 publishedat IEEE Globecom 2017 [43].

Building on these results, we challenge the idea of a fixed sampling frequency and present a lightweight, 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 under submission to the IEEE Trans. on Mobile Computing (TMC) journal and also registered at Hal Inria as the Research Report [36]. It represents the final contribution of the collaboration with Marco Fiore, Panagiota Katsikouli, who spent 5 months in our team working as an internship in 2017, and Diego Madariaga who spent 3 months in 2018 in our team working as an internship).

8.11.5 Data offloading decision via mobile crowdsensing

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

It is known that mobile network operators are struggling to keep up with such traffic demand, and part of the solution is to offload communications to WiFi networks. Mobile data offloading systems can assist mobile devices in the decision making of when and what to offload to WiFi networks. However, due to the limited coverage of a WiFi AP, the expected offloading performance of such a system is linked with the users mobility.

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) [45]. 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 under submission at the IEEE Trans. on Mobile Computing (TMC) journal.

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

8.11.6 Identifying how places impact each other by means of user mobility

Participants: Lucas Santos de Oliveira *(EMBRACE)*, Pedro Olmo Stancioli *(Federal U. of Minas Gerais)*, Aline Carneiro Viana.

The way in which city neighborhoods become popular and how people trajectory impacts the number of visitation is a fundamental area of study in traditional urban studies literature. Many works address this problem by means of user mobility prediction and PoI recommendation.

Different from previous literature, in this work, we are interested in understanding how the neighborhood PoI affect each other by means of human mobility using location-based social networks (LBSNs) data source. In this context, we propose a methodology to quantify the power of point-of-interests (PoIs) in their vicinity, in terms of impact and independence – the first work in the literature (to the best of our knowledge). We modeled POI's visits using the multiflow graph model where each POI is a node and the transitions of users among PoIs are a weighted direct edge.

Using this multiflow graph model, we compute the attract (i.e., the capacity of a PoI to receive people from its vicinity), support (i.e., the capacity of a PoI to disseminate people over its vicinity), and independence (i.e., the potential resilience a PoI has to other PoIs moving out (closing their doors) from its neighborhood) powers of PoIs. Our findings show that in University campus: (i) buildings have low support and attract; (ii) people tend to move over a few buildings and spend most of their time in the same building; and (iii) there is a slight dependence among buildings, even those with high independence receive user visits from other buildings on campus. Globally, we reveal that: (i) our metrics capture places that impact the number of visits in their neighborhood; (ii) cities in the same continent have similar independence patterns; and (iii) places with a high number of visitation and city central areas are the regions with the highest degree of independence.

This work was first published in ACM MobiWac [49] and its extended version published at ACM Transactions on Knowledge Discovery from Data (TKDD) journal [6], also registered at Hal Inria as the Research Report [32]. Lucas did an internship in our team from Nov. 2019 to Jan. 2020. He is currently working on the SafeCityMap Inria mission COVID project.

8.11.7 Tactful opportunistic forwarding: What human routines and cooperation can improve?

Participants: Rafael Lima da Costa *(CAPES)*, Aline Carneiro Viana, Leobino Sampaio *(Federal U. of Bahia)*, Artur Ziviani *(LNCC)*.

According to literature, one of the 10 key enabling technologies for 5G is device-to-device (D2D) communications, an approach based on direct user involvement. User-centric communication arose as an alternative to increase capillarity and to offload data traffic in cellular networks through opportunistic connections among users. Although having the user as main concern, solutions in the user-centric communication/networking area still do not see the user as an individual, but as a network active element.

In this work, we first introduce the Tactful Networking paradigm, whose goal is to add perceptive senses to the network, by assigning it with human-like capabilities of observation, interpretation, and reaction to daily-life features and involved entities. To achieve this, knowledge extracted from human inherent behavior (routines, personality, interactions, preferences, among others) is leveraged, empowering user-needs learning and prediction to improve QoE while respecting privacy. We survey the area, propose a framework for enhancing human raw data to assist networking solutions and discuss the

tactful networking impact through representative examples. This tutorial paper was published at the IEEE Transaction on Emerging Topics in Computational Intelligence in 2020 [42].

Then, we study "What type of knowledge can we extract from human mobility routines behavior to leverage opportunistic communication services or protocols?". The extracted metrics represent different types of knowledge extracted from people routine present in their movements. Because of the strong routine component of human mobility, such metrics capture different but recurrent behaviors on wireless encounters between mobile users. The results show heterogeneity in metric coefficients and contact occurrence and duration in different periods of the day, highlighting the need for characterizing traces before their use. This preliminary study was published at the UrbComp 2020 workshop (jointly with DCOSS) [46].

There is a lack of initiatives beyond traditional techniques or limited human-mobility features to identify routines (spatiotemporal patterns), related consequences (e.g., wireless encounters), and movement decisions (e.g., motion direction) with more granularity and precision. We tackle such limitations by combining the metrics extracted (our previous work) from a real-world and a synthetic dataset and applying them into a novel Tactful Opportunistic cOmmunicaTion Strategy (TOOTS). This strategy features *a dissemination policy and a forwarding algorithm*. In the former, users' spatiotemporal properties and induced wireless encounters are leveraged to choose content-disseminating nodes that have shown previous encounter routine with destination nodes. The forwarding algorithm relies on nodes' popularity, displacement, network-cell (as PoIs) visiting and proximity, and displacement direction. TOOTS reaches 100% delivery rate with respectively 28%, and 73% less delivery latency, and with 16%, and 27% less overhead in the real-world and synthetic datasets.

This work was published at the AINA 2021 conference [18] and an extended version is under the 2nd round of review at the Computer Communication journal. Rafael Lima da Costa did a joint PhD between the Federal Univ. of Bahia and Inria/IPP, under my co-supervision. He defended in July 2021 and his manuscript is available in [25].

8.11.8 Deciphering Predictability Limits in Human Mobility

Participants: Douglas do Couto Teixiera, Aline Carneiro Viana, Jussara Almeida *(Federal U. of Minas Gerais)*, Mario S. Alvim *(Federal U. of Minas Gerais)*.

Measuring the predictability of human mobility is a hard task due to the uncertain and heterogeneous behavior of humans, as well as to the variability of parameters influencing such behavior. Besides, literature on mobility predictability is based on a sophisticated compression algorithm whose output bears little resemblance to its input, making it hard to understand what makes one's mobility more or less predictable. If better interpretable, *we believe an accurate predictability with short-history of movements can be computed*. Because of such compression strategy, they lack extensibility in considering contextual information (e.g., hours of the day, weather, friends' mobility). As contextual information is expected to grow, thanks to the popularity of IoT devices and on-line social networks, it is paramount to find ways to add such information in predictability estimates.

In this research activity, we first establish the theoretical foundations for the computation of interpretable and extensible predictability of mobility. We propose a new measure, *regularity*, which together with *stationarity*, helps us understand what makes a person's mobility trajectory more or less predictable. Those metrics are complementary and jointly are able to explain most of the variation in the main state-of-art predictability approach. Additionally, we investigate strategies to incorporate different types of contextual information into predictability estimates, and show that the benefits vary depending on the underlying prediction task. Our results show that, for the next place prediction problem, the use of contextual information plays a larger role than one's history of visited locations in estimating their predictability.

This work was published at ACM SIGSPATIAL 2019, a A+-ranked conference in our domain, and was indicated as a top-six best paper candidate. There is *no study in the mobility condition that ensure a general computation of a context-enhanced predictability, as we proposes to do.*

We then extend the SigSpatial published work by revisiting this state-of-the-art method, aiming at tackling interpretability and extensibility limitations of predictability. We introduce a novel strategy that

seamlessly incorporates contextual information into the main state-of-the-art predictability technique. A broad evaluation and discussion of the benefits of contextual information on several entropy estimators, for both next-cell and next-place prediction. Our results show that introducing context information can indeed improve predictability estimate, when simpler, alternative entropy estimators are employed. However, results also hint at the observation that using context may not always bring benefits to predictability estimate in practical scenarios. This work extension was published at the ACM Transactions on Spatial Algorithms and Systems (TSAS) journal [9], following an invitation of the Editor in Chief resulting from the top-six best paper selection at ACM SigSpatial. A related report can be found in Hal Inria [9].

Going forward, we propose to view human mobility as consisting of two components, routine and novelty, with distinct properties. We propose a technique that allows us to (i) quantify the effect of novelty on predictability, and (ii) gauge how much one's routine deviates from a reference routine that is completely predictable, therefore estimating the amount of unpredictable behavior in one's routine. Our experiments show that routine behavior can be largely explained by three types of patterns: (i) stationary patterns, in which a person stays in her current location for a given time period, (ii) regular visits, in which people visit a few preferred locations with occasional visits to other places, and (iii) diversity of trajectories, in which people change the order in which they visit certain locations.

This work extension was published at EPJ Data Science journal [8], a related report can be found as well in Hal Inria [38].

Douglas Teixeira did a joint PhD between the Federal Univ. of Minas Gerais and Inria/Polythecnic School-IPP, under my co-supervision. He defended in July 2021 and his manuscript is in [52] [26].

8.11.9 Identifying and profiling novelty-seeking behavior in human mobility

Participants: Licia Amichi, Aline Carneiro Viana, Mark Corvella *(Boston Univ.)*, Antonio F. Loureiro *(Federal U. of Minas Gerais)*.

Individuals' mobility prediction models are unable to capture uncertainties in the mobility behavior of individuals, and consequently, suffer from *the inability to predict visits to new places*. This is due to the fact that current models are oblivious to the exploration aspect of human behavior. We focus on such phenomenon, which has rarely been tackled in the literature but indeed, represents a real issue. We first work on the understanding of the exploration phenomenon and answer the following question: *What type of visits characterize the mobility of individuals?*. We show that a two-dimensional modeling of human mobility, which explicitly captures both regular and exploratory behaviors, yields a powerful characterization of users. Using such model, we identify the existence of three distinct mobility profiles with regard to the exploration phenomenon – *Scouters* (i.e., extreme explorers), *Routiners* (i.e., extreme returners), and *Regulars* (i.e., without extreme behavior). Our results unveil important novelty preferences of people, which are ignored by literature prediction models. We then discuss how our profiling methodology could be leveraged to improve prediction.

This first work was published at the Student workshop of ACM CONEXT 2019 and in the French Algotel conference 2020 [41]. An extended version was then published at the ACM SigSpatial 2020 [40]. A journal under submission to the IEEE Transactions on Emerging Topics in Computing, where we evaluate the impacts of novelty-seeking and the prediction task formulation on the theoretical and practical predictability extents. A technical report on this last work is available at Hal Inria [27, 28].

Next, we claim the tackling of such limitation first requires identifying the purpose of the next probable movement. In this context, we propose a novel framework for adjusting prediction resolution when probable explorations are going to happen. In fact, the geographical occurrences of explorations are far from being random in a coarser-grained spatial resolution. Exploiting these properties, instead of directly predicting a user's next location, we design a two-step predictive framework. First, we predict the mobility purpose of an individual: (i) a *return*, i.e., a visit to a previously known location, or (ii) an *exploration*, i.e., a discovery of a new place. Next, we predict the next location or the next coarse-grained zone depending on the inferred type of movement. The results demonstrate substantial improvements in the accuracy of prediction by dint of fruitfully forecasting coarse-grained zones used for exploration activities.

This work was published at the ACM SigSpatial 2021 [10].

Licia Amichi did a PhD under my supervision. She defended in November 2021 and the final version of her manuscript will be on-line from Feb. 2022.

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

When performing analytics from collected data related to smartdevices, privacy issues comes 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.

8.12.1 Public Wireless Packets Anonymously Hurt You

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

With growing privacy concerns over the last decade, two of the most notable wireless technologies – i.e., BLE and WiFi – are being investigated more in terms of privacy vulnerabilities. To this regard, steps were taken by the standard, notably *MAC address randomization*, to address these concerns. *MAC address randomization* can hide the device's identity to some extent. This feature has been the backbone of user privacy in wireless networks, especially BLE and WiFi. However, most of the existing related works suggest flaws in randomization or suggest inferring insights from the transmitted public data in the packets. Unfortunately, such solutions are not feasible due to resource constraints. *To the best of our knowledge, none of current work give a global view on the privacy issues in the design of public wireless packets itself. Current works do not look into counter-measures of timing-based attacks, which are more generic and effective than we would see in the upcoming sections.*

The novelty of this contribution lies in the investigation of the root causes of growing privacy concerns in public wireless packets. The key contributions are 1) Classification of current attacks in the literature based on methodology 2) Revealing key design flaws in current WiFi and BLE public packets 3) Solutions and recommendations to rectify the flaws we detect in the design.

This work is related to ANR MITIK project (2020-), described in its ANR annual report and also published in LCN 2021 [17].

8.12.2 SimBle: a tool to generating privacy preserving real-world BLE traces with ground truth

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

Bluetooth has become critical as many IoT devices are arriving in the market. Most of the current literature focusing on Bluetooth simulation concentrates on the network protocols' performances and completely neglects the privacy protection recommendations introduced in the BLE standard. Indeed, privacy protection is one of the main issues handled in the Bluetooth standard. For instance, the current standard forces devices to change the identifier they embed within the public and private packets, known as MAC address randomization. Although randomizing MAC addresses is intended to preserve device privacy, recent literature shows many challenges that are still present. One of them is the correlation between the public packets and the emitters. Unfortunately, existing evaluation tools such as NS-3 are not designed to reproduce this Bluetooth standard's essential functionality. This makes it impossible to test solutions for different device-fingerprinting strategies as there is a lack of *ground truth* for large-scale scenarios with the majority of current BLE devices implementing MAC address randomization. In this paper, we first introduce a solution of standard-compliant MAC address randomization in the NS-3 framework, capable of emulating any real BLE device in the simulation and generating real-world Bluetooth traces. In addition, since the simulation run-time for trace-collection grows exponentially with the number of devices, we introduce an optimization to linearize public-packet sniffing. This made the large-scale trace collection practically feasible. Then, we use the generated traces and associated

ground truth to do a case study on the evaluation of a generic MAC address association available in the literature [16]. Our case study reveals that close to 90% of randomized addresses could be correctly linked even in highly dense and mobile scenarios. This prompts the BLE standard to be revisited on privacy-related provisions. We provide privacy recommendations based on our case study. Finally, we discuss the consequences that real randomized traces bring to different scientific research domains and how our proposed solution helps in overcoming new challenges.

This work is related to ANR MITIK project (2020-) and a preprint work is availalbe at HAL-inria [37] and a paper was published in [19].

8.12.3 Detecting and simulating 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 at the IEEE Communication and Tutorial Surveys journal and a technical report can be found at Hal Inria under the reference: hal-03105845 [4].

Currently, we are working on the SIMBoxFraudSimulator, an open-source simulator of SIMBox fraud strategies and detection methods in LTE networks. 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. The aim is to deploy existing detection methods of the literature for extensive evaluations to highlight their limitations and allow to propose more accurate and rapid-evolving detection approaches. This simulator is mentioned in the Software section and can be found at Inria GitLab.

8.13 Geometry of virus exposure [Axis 2]

Participants: Philippe Jacquet, Liubov Tupikina.

The Ariadne Covid is a 2020 project whose aim was to create an application which provides a secured path for outdoor excursion with limited virus exposure during covid lockdowns. The algorithm is based on random walks and has the property to balance the density in streets. This effect counters the social tendancy which triggers the people to gather in the same locations and multiplies the risk of infection, indeed the random walk can reduce the risk by a factor 3 or 6. In 2021, we have extended the Ariadne covid concept to the daily commuting in a city after lockdown when the virus is still present and dangerous. In this context the random walk is not operant because the commuting path must be aimed to a given destination (home, workplace). The use of the shortest path algorithm is not good because it does not provide enough path diversity, furthermore it turns out to be far too complex for a portable application because of its quadratic cost. The algorithm has been simulated on the map of Kaliningrad, the old Koenigsberg, whose sophisticated bridge network has inspired to Euler the premise of the graph theory.

This work has been published in [15].

8.14 SafeCityMap: From spatiotemporal mobility of our society to the COVID propagation understanding. [Axis 2]

Participants: Aline Carneiro Viana, Artur Ziviani *(LNCC)*, Haron Calegari Fanteceli *(LNCC,Inria)*, 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 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. Contrary, to regions or country-wide resolution, the data describes population mobility flows among zones ranging from 0.025 km to 5.40 km, corresponding to 326 aggregated zones over the total area of 93.76 km2 of the city of Paris.

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, 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.

This work is under major submission at the ACM Transactions on Spatial Algorithms and Systems and a report can be download at [33].

8.15 Energy balance in urban wireless ad hoc network [Axis 1]

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

We have studied the energy balance of wireless end to end transmissions in multihop setting. We use the hyperfractal traffic density model which is particularly well adapted to city. The principle of the hyperfractal model is based on the fact that streets of low density tends to be dense in the street network of a modern city. A hyperfractal density measure has a fractal dimension which contrary to classic fractal set can be larger than the dimension of the embedding Euclidian space (for instance 2). The energy balance show that the end to end transmission energy in a long multihop routing path tends to zero and tends faster to zero if we allow to increase the transmission delay.

This work has been published in [48].

8.16 Wireless 5G transmission supported by drones [Axis 1]

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

We investigated moving networks of Unmanned Aerial Vehicles (UAVs) to extend connectivity and guarantee data rates in the 5G by analysing possible hovering locations based on their specific limitations such as flight time and coverage. We provide theoretical limits in terms of connectivity extension for vehicular networks served by fixed Enhanced Mobile BroadBand (eMBB) infrastructure, in hyperfractal geometry. In particular we show that a number of base station proportional to the square root of the number of mobile nodes is sufficient to cover most of the mobile nodes by a single hop, and extending this coverage by drones would induce a marginal cost.

This work has been published in [47].

8.17 Analytic Learning theory, frugal AI [Axis 2]

Participants: Philippe Jacquet, Gil Shamir, Wojciech Szpankowski.

On one side of the landscape, machines can learn, but like human brain, have learning limitations. On the other side of the landscape, computer science has developed a large spectrum of efficient and basic algorithms, mainly because in the first place the human brain computational ability could not match. But in between some problems are just hopelessly un-learnable, *e.g.* the program halting problem or the pure random parity functions. Some problems are just hard to learn because it would take an exponential time to converge, or simply won't converge because of a bad initialization of the learning process. In this case given a class of problems, it is important to be able to characterize the decay rate of the regret of a learning method. Our vision is an augmented learning theory as the first step toward the creation of an AI which can achieve efficient learning but with much more limited resource such as those which can be mobilized in the context of ioT.

More precisely, we want to achieve a "minmax" analysis. Assuming a training set of size T we denote R_T^* a min max regret. *i.e.* there always exist a problem for which the regret will be greater than R_T^*. The determination of R_T^* is based on combinatorics and analytic information theoretic tools. This methodology is powerful, as argued by Andrew Odlyzko: "Analytic methods are extremely powerful and when they apply, they often yield estimates of unparalleled precision". We have applied this methodology to logistic regression.

This work has been published in [35].

9 Bilateral contracts and grants with industry

9.1 Bilateral grants with industry

Nokia (ADR): Network Information Theory

Participants: Cedric Adjih, Iman Hmedoush.

Through the common Inria-Nokia laboratory, the team is involved in the action "Network Information Theory" (ADR, "Action De Recherche"). In collaboration with Nokia, and Inria EPI MARACAS, and EPI EVA, we are working on the subject of optimization and evaluating communications for IoT networks. This includes 5G and beyond, medium-access level/random access techniques protocols, modern random access and applying machine learning techniques to wireless communications.

10 Partnerships and cooperations

10.1 International initiatives

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

PSAR

Title: Physical Security Applied to (R)IOT

Duration: 2022 ->

Coordinator: Schiller Jochen (Jochen.Schiller@fu-berlin.de)

Partners:

- Freie Universität Berlin

Inria contact: Emmanuel Baccelli

Summary: PSAR extends the collaboration between FU Berlin and Inria on new topics in the domain of IoT cybersecurity.While chips are manufactured precisely enough to provide identical digital functions, the silicon still has nano-variations from one chip to another, even if it is the same model from the same manufacturer. Work planned in PSAR aims to leverage tiny variations in propagation delays in transistors and wires on IoT devices to provide physically unclonable functions (PUFs) which could be used for device challenge-response authentication, instead of using a secret key. On the other hand, leveraging both advanced authentication and secure networking, PSAR plans to work on approaches and mechanisms enabling periodic and holistic ”health checks” for IoT deployments that are up and running. One part of this work will consist in defining practical sets of health indicators. Another part will consist in the design, implementation and testing of mechanisms enabling robust measurements of these indicators.Collaboration planned in PSAR also aims to participate actively in the the evaluation and selection of cryptographic primitives appropriate for post-quantum resistance on microcontroller-based IoT devices.

MLNS2

Title: Machine Learning, Network, System and Security

Duration: 2021 ->

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.

10.1.2 Participation in other International Programs

PHC-Utique 2021 - 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: Started in 2021

10.2 International research visitors

10.2.1 Visits of international scientists

Inria International Chair: No chair.

Other international visits to the team

- Leila Saidane and Ichrak Amdouni

  Status: Researcher

  Institution of origin: ENSI

  Country: Tunisia

  Dates: 18-22 oct. 2021

  Context of the visit: progress on the Project "Precision Agriculture in the era of Drones and Artificial Intelligence"

  Mobility program/type of mobility: PHC Utique 21G1116

- Luca Pappalardo

  Status: Researcher

  Institution of origin: Institute of Information Science and Technologies of the National Research Council of Italy (ISTI-CNR), Pisa

  Country: Italy

  Dates: 22-25 nov. 2021

  Context of the visit: PhD defense of L. Amichi and discussions on: mobility analystics and prediction; scikit-mobility code contribution; calls for long-stay visits (on proposal submitted for the call "Invited Professor" Digicosme 2022)

  Mobility program/type of mobility: team resource for on-going PhDs

10.2.2 Visits to international teams

Sabbatical program: No sabbatical program.

Research stays abroad

- Cédric Adjih

  Visited institution: ENSI / Université de la Manouba

  Country: Tunisia

  Dates: 12-18 dec. 2021

  Context of the visit: progress on the Project "Precision Agriculture in the era of Drones and Artificial Intelligence"

  Mobility program/type of mobility: PHC Utique 21G1116

10.3 European initiatives

10.3.1 FP7 & H2020 projects

H2020 SPARTA project

Participants: Emmanuel Baccelli, , Francois-Xavier Molina.

- Program: H2020 SU-ICT-03-2018: Establishing and operating a pilot for a Cybersecurity Competence Network to develop and implement a common Cybersecurity Research & Innovation Roadmap
- Project acronym: SPARTA
- Project title: Strategic Programs for Advanced Research and Technology in Europe
- Duration: 2019-2022
- Participant from TRiBE: Emmanuel Baccelli, Francois-Xavier Molina
- Other partners include CEA, TU Muenchen, IMT among many others
- Abstract: The Sparta project is a 3-year H2020 project started in February 2019, which will put in motion a competence network on cybersecurity, with a view to shape a future EU-wide cybersecurity agency. In more details: TRiBE participates on topics around low-power IoT security, whereby RIOT is used as the base platform on top of which advances will be experimented with and made available in practice.

10.3.2 Other european programs/initiatives

TinyPART

Participants: Emmanuel Baccelli, , Cedric Adjih, , Koen Zandberg.

- Program: ANR/BMBF French German Cybersecurity Project
- Project title/acronym: TinyPART
- Duration: 2021-2024
- Other partners include Orange, FU Berlin, Lille University and PHYSEC GmbH

- Abstract: TinyPART aims to develop Software-Defined IoT building blocks for a deeply embedded software platform fitting low-power devices, architectured for privacy-by-design and cybersecurity. TinyPART seeks to provide both capabilities to isolate small runtime containers of untrusted (possibly scripted) IoT logic, and adequate privacy-oriented preprocessing (such as differential privacy and lightweight cryptographic tools) of IoT data on-board, before it is transferred from the OS to the container(s) and/or from the containers to the cloud. The goal of TinyPART is thus to explore tradeoffs between isolation guarantees, the logic orchestration functionality and security, memory footprint and ease of use by non-specialist embedded systems developer. In practice, TinyPART bases its embedded development on the open source operating system RIOT and the protokernel PIP. TinyPART is a German-French research project on cybersecurity jointly sponsored by the German Ministry of Education and Research and the French National Research Agency.

10.4 National initiatives

Equipex FIT:

Participants: Cedric Adjih, Alexandre Abadie *(Inria, SED)*, 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) aims to develop 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 gives 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. FIT was one of 52 winning projects from the first wave of the French Ministry of Higher Education and Research's "Équipements d'Excellence" (Equipex) research grant program, in 2011.
  One component of the FIT platform 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, Webdyn
- 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

10.4.1 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: 2020–2024
- Coordinator: Aline Carneiro Viana
- Other partners: COMETE/Inria, Universite de la Rochelle, Sorbonne Universite (UPMC).
- 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.

10.5 Regional initiatives

VehiCloud

Participants: Andrea Araldo *(Télécom SudParis - SAMOVAR)*, Lila Boukhatem *(LISN Univ. Paris Saclay)*, Nadjib Achir, Aline Carneiro Viana.

- Funding instrument/scientific committee: DigiCosme
- Project acronym: VehiCloud
- Project title: How can Vehicles increase Cloud intelligence?
- Duration: 2021–2024
- Coordinator: Andrea Araldo
- Other partners: Télécom SudParis - SAMOVAR, LISN Univ. Paris Saclay.
- Abstract: The objective of this PhD project is to answer to the questions: ***What is Vehicular Cloud (VCC) good for? And under which conditions?***. We propose to evaluate the benefits of integrating VCC into future network architectures, together with CC (Cloud Computing) and EC (Edge Computing). We translate these high level questions into concrete operational objectives as follows. We assume mobile users generate tasks of different traffic classes, defined in terms of latency constraints (high vs. low *responsiveness*) and bandwidth requirements (data-intensive vs. data-light). The key challenges that we need to tackle are: **(i)** Extremely **large scale** of the Computation Ecosystem (CoE) and **heterogeneity** of its computation nodes, in terms of mobility, connectivity and amount of computation resources. **(ii)** The CoE is **highly dynamic and stochastic**: resources available and quality of connections change over time and cannot be exactly known. **(iii) Applications diversity**, in terms characteristics, structure and constraints.

Mobility-enhanced MEC

Participants: Nadjib Achir, Aline Carneiro Viana.

- Funding instrument/scientific committee: Inria ADT
- Project title: How mobile can a Mobile Edge Computing be?
- Duration: 2020-2022
- Coordinator: Aline Carneiro Viana
- Other partners: Federal Univeristy of Rio de Janeiro (UFRJ), Brazil
- Abstract: Distributed and in-network computation at the edges is considered a key factor to reduce energy consumption and the long and fluctuating access delay incurred when using far away clouds. A direct consequence of this computation at the edge is their exposure and sensitivity to user mobility, which may render the location of the used edge computation non-optimal in the long run : Implying extra latency and energy consumption. According to such considerations, our main objective is to set up **an experimental platform in the Grid'5000 cloud computing facilities**, in which it is possible to evaluate the **impact of the mobility** on the energetic loss and latency increase/variation when **task offloading to a Mobile Edge Computing (MEC) system** is considered. This platform should follow the recommendations of the ETSI MEC (Multi-Access Edge Computing) standards to guarantee the proper dissemination and adoption of the proposed platform by the research community. Finally, to be able to support large-scale scenarios, we aim to deploy this platform as part of the Grid'5000 cloud computing facilities, which allow us to take advantage of the Grid'5000 monitoring tools for resource usage and energy consumption.

11 Dissemination

Cédric Adjih, Emmanuel Baccelli, Nadjib Achir, Philippe Jacquet, Aline Carneiro Viana, Anne Josiane Kouam

11.1 Promoting scientific activities

- Emmanuel Baccelli coordinated the conception and the writing of the Inria White Book on IoT, which was published in December 2021.

11.1.1 Scientific events: organisation

- Emmanuel Baccelli and Koen Zandberg co-organized the SUIT hackathon at IETF 112, in November 2021.

General chair, scientific chair

- Nadjib Achir: General chair of the 12th Wireless Days Conference (WD 2021), 30 June to 02 July – 2021, Paris, France (Virtual Conference)
- Aline C. Viana: Shadow Algotel & CoRes 2020 and 2021 GDR Rescom (French working group) – shadows TPCs aiming at providing an educational experience for young PhD graduates, post docs, and junior researchers by simulating a TPC meeting entitled to discuss some papers submitted to the related conferences.

Member of the organizing committees

- Nadjib Achir: Publicity chair in the 19th ACM Conference on Embedded Networked Sensor Systems SenSys2021, November 15 – 17, 2021, Coimbra, Portugal.
- Nadjib Achir: Workshop chair in the 30th European Conference on Networks and Communications 2021 EuCNC, 9-11 June 2021.
- Aline C. Viana: (1) Workshop co-chair of IEEE MASS 2021; Sponsorship co-chair of ACM SenSys 2021;

11.1.2 Scientific events: selection

- Cédric Adjih: TPC co-chair of PEMWN 2021.

Chair of conference program committees

- Nadjib Achir: General co-chair of WD 2021.
- Aline C. Viana: co-chair of Shadow TPC of Algotel/Cores in 2020 and 2021

Member of the conference program committees

- Cédric Adjih: CCNC 2022 NG-ROWS, Globecom 2022 NGNI, ICC'22 NGNI, ICC'22 CCNS.
- Emmanuel Baccelli: PEMWN 2021, DAI-SNAC CoNEXT 2021 Workshop, RIOT Summit 2021
- Aline C. Viana: (1) Algotel 2022;
- Worth to highlight: the PhD student Anne Josiane Kouam was member of two Artifact Evaluation Committees (AEC) of two top-ranking conferences USENIX Security 2022 and Eurosys 2021.

Reviewer

- Cédric Adjih: PEMWN 2021, MSWiM'21, Globecom 2021, COMSETNAT 2021, Wireless Days 2021, NCC 2021, ICC'21 (WS01 COVI-COM and WC Symposium).
- Nadjib Achir: PEMWN 2022, PEMWN 2021, Globecom 2021, EuCNC 2021, Wireless Days 2021, ICT 2021, ICC 2021.

11.1.3 Journal

Member of the editorial boards

- Philippe Jacquet is member of the editorial board of the Journal of Discrete Mathematics and Theoretical Computer Science.
- Aline C. Viana:
  - (since Jul. 2019 -Apr 2021) Editorial Board member of *Ad Hoc Networks Elsevier Journal*.
  - (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

- Cédric Adjih, IEEE Transactions on Communications, Journal of Network and Systems Management,
- Philippe Jacquet has reviewed for many journals, the most exotic journal has been Springer Nature Applied Sciences.
- Emmanuel Baccelli has reviewed for Elsevier SoftwareX, Elsevier Future Generation Computer Systems.
- Nadjib Achir has reviewed for Computer Networks, IEEE Transactions on Vehicular Technology.
- Aline C. Viana: for Elsevier Science & Justice; Elsevier Transport Policy.

11.1.4 Invited talks

- Emmanuel Baccelli gave a keynote at the International Conference on Availability, Reliability and Security (ARES 2021) on "Cyber-Secure Building Blocks for Low-Power IoT".
- Aline C. Viana: (1) Keynote: LastMile2021 workshop (Jan/2021). (2) Invited speaker: Talk at Brazilian Computer Society conference (CSBC) joint with 13º Brazilian Symposium of Ubiquitous and Pervasive Computing (SBCUP) (Jun 2021). (3) Invited seminars: for Brazilian IEEE ComSoc researchers representing the Brasilia University (UnB, Brazil) and the Center-Nord region in Brazil (Jul 2021); and two seminars for master and PhD students of PUC-MG (Brazil), May 2021.

11.1.5 Research administration

- Aline C. Viana: (1) the leader of the TRiBE Project-Team of Inria since its creation (Jul.2019); She was the leader of the previous INFINE project-tem for one year 2018-2019; (2) the coordinator of ANR MITIk (since 2020-) and SafeCityMap Inria-Covid mission project (since 2020-);

11.2 Teaching - Supervision - Juries

11.2.1 Teaching

- Master : Emmanuel Baccelli, “IoT & Security”, summer semester seminar (April 2021 - June 2021), Freie Universitaet Berlin.
- Master : Emmanuel Baccelli, “Operating Systems for Small Connected Devices in the Internet of Things”, cours magistral, Formation PESTO Corps des Mines, Telecom ParisTech, Paris France. Sept. 2021.
- Nadjib Achir is associate professor at the Sorbonne Paris Nord University and do his full service at the university.
- 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

11.2.2 Supervision

- PhDs supervision
  - PhD, defended on 22 Nov. 2021: Hirah Malik, "Efficient COding of Meta-information in Information-CEntric NEtworks", since Oct. 2017. Advisors: C. Adjih, Michel Kieffer, and Claudio Weidmann.
  - PhD, defended on 15 Dec. 2021: Célia Tazibt, " Data collection through UAV", Advisors: Nadjib Achir and Tounsia Djamah.
  - PhD in progress: Iman Hmedoush, "Connection protocols for the 5G IoT", since Oct. 2018. Advisors: C. Adjih and Paul Mühlethaler.
  - PhD in progress: Hadi Yakan (UVSQ), "Security of V2X Communications in 5g networks", since Sep. 2019. Advisors: N. Aitsaadi, I. Fajjari, and C. Adjih.
  - 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: Koen Zandberg, "Cybersecure Multi-Tenant Microcontroller-based IoT", since March 2020. Advisor: Emmanuel Baccelli.
  - PhD in progress: Rosario Patane, "VehiCloud: How can Vehicles increase Cloud intelligence?", since Dec. 2021. Advisors: Lila Boukhatem, Andrea Araldo, Nadjib Achir.
  - PhD in progress: IPP, Abhishek K. Mishra, "Detection of bypass frauds in cellular network datasets", since Nov 2019. Advisor: Aline C. Viana and Nadjib Achir.
  - PhD in progress: IPP, Anne Josiane Kouam Djuigne, "Detecting and simulating bypass SIMBox frauds in cellular networks", since Nov 2019. Advisor: Aline C. Viana and Alain Tchana.
  - PhD in progress: LNCC (Brazil), Haron C. Fantecele , "Mobility modeling and prediction through flow model", since Feb. 2020. Advisor: Aline C. Viana and Antonio Tadeu (LNCC).
  - PhD defended in Nov. 2021: IPP (Institut Polytechnique de Paris), Licia Amichi, "From movement purpose to perceptive spatial mobility prediction". Advisor: Aline C. Viana. Collaborators: Mark Crovella (Boston Univ.) and Antonio F. Loureiro (UFMG).
  - PhD defended in Aug. 2021: Jointly IPP and Federal University of Minas Gerais. Douglas Teixeira, "Predictability in Human Mobility: Interpretability, Extensions and Applications", since April 2018. Advisor: Aline C. Viana and Jussara Almeida (UFMG).
  - PhD defended in Aug. 2021: Jointly IPP and Federal University of Bahia. Rafael Costa, "Tactful Networking as a Cornerstone for Opportunistic Human-Aware D2D Communication", since May 2017. Advisor: Aline C. Viana and Leobino Sampaio (UFBA).
- 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.
- Mentoring program implication: A. C. Viana is a co-coordinator of this program at Inria Saclay, sibling the mentoring of permanent researchers/associate professors and post-docs of the center; P. Jacquet and A. C. Viana act as *"researcher mentors"* in this program; N. Achir participates as *"mentoree"* in the same program.

11.2.3 Juries

- Nadjib Achir (Reviewer): PhD defence of Giacomo Quadrio, Delivery of High Quality and Interactive Multimedia Contents over the Internet, University of Padova, jnavier 2021.
- Nadjib Achir (Reviewer): PhD defence of Fouzi Boukhalfa, Low Latency Radio And Visible Light Communications for Autonomous Driving, October 2021.
- Aline C. Viana was a reviewer (rapporteur) for the committees of the following PhD student: Noudéhouénou Lionel J.Houssouv (Univ. de La Rochelle Jul. 2021);
- Aline C. Viana was an examiner for the mi-term committees of the following PhD student: Ludovic Javet (UPSaclay-Univ. de Verasille, Nov. 2021)
- Aline C. Viana was an examiner for the mi-term committees of the following Master student: Marcos Felipe Barboza (Univ. Federal of Goias, July 2021)

11.3 Popularization

11.3.1 Internal or external Inria responsibilities

- Philippe Jacquet has contributed to the organization of the Telecom pole in the EPP research team grouping
- For Aline C. Viana:
  - At Inria:
    - (since 2019) member of the Evaluation Commitee (CE) of Inria. CE exercises the skills that are devolved to it by the staff of Inria. It prepares the work of the Scientific Council by contributing in particular to defining the orientations of the Institute's activities.
    - (since Sep. 2017) Aline C. Viana is a member of BCEP, evaluating Inria teams in process of creation, discussing main issues related to different scientific commissions, discussing changes in the institution.
    - (since Dec. 2018) Aline C. Viana is co-Coordinator of the mentoring program for researchers at Inria Saclay (Inria Saclay mentoring program). The program goal is the coach of junior researchers by more experienced ones in order to provide them with a complementary perspective for their career, independently of any hierarchical link.
    - member of Inria researcher selection and promotion juries committees: CRCN (admission jury); DR0 2020, DR2 2021; DR1 2021; CRHC 2022.
  - At the regional eco-system:
    - (Oct 2020-Oct 2021): Co-chair of the "Distributed Networks" subject at the Digicosme COMEX (2020-): Digicosme is an Excellence Laboratory Center in digital science funded by the Ministry of Higher Education and Research as part of Future Investment Program (FIP), and supported by Université Paris-Saclay.
  - Other committees:
    - (2022) Member of the Selection Committee for an Assistant Professor position at the ENS-Lyon'.
    - (2021) Member of the Selection Committee for an Assistant Professor position at the IUT/Université de La Rochelle".
- Cédric Adjih is member of the "Formation" commission of Digicosme. He is also member of the Hub "Digital Infrastructure and IoT" of Systematic.

11.3.2 Education

- Aline C. Viana: co-chair of Shadow TPC of Algotel/Cores in 2020 and 2021, aiming to train PhD students and Por-Doc fellows to the reviewing process in conferences.

11.3.3 Interventions

- Philippe Jacquet has made a presentation to the CISS workshop organized by John Hopkins university on the limitation of learning in AI.
- Aline C. Viana: General public: Inria Unithé au Café (Jan/2021).
- Worth to highlight: a pupularization talk (on "Qu'est-ce que le métier de chercheur ?") and a video production (on "Wireless Communications") were performed by the PhD student Anne Josianne Kouam, as member of the scientific popularization team of INRIA Saclay.

12 Scientific production

12.1 Publications of the year

International journals

[1] C. Dumas, L. Salaün, I. Hmedoush, C. Adjih and C. Shue Chen. 'Design of Coded Slotted ALOHA with Interference Cancellation Errors'. In: *IEEE Transactions on Vehicular Technology* (2021). URL: https://hal.inria.fr/hal-03266615.

[2] V. GONÇALVES BRAGA, S. L. CORREA, K. VIEIRA CARDOSO and A. Carneiro Viana. 'Data-Driven Characterization and Modeling of Web Map System Workload'. In: *IEEE Access* (2021). DOI: 10.1109/ACCESS.2021.3058622. URL: https://hal.inria.fr/hal-03141754.

[3] I. Hmedoush, C. Adjih, K. Khawam and P. Mühlethaler. 'A Game Theoretic Approach to Irregular Repetition Slotted Aloha'. In: *IEEE Access* 10 (5th Jan. 2022), pp. 4600–4614. DOI: 10.1109/ACCESS.2022.3140495. URL: https://hal.inria.fr/hal-03533559.

[4] 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). URL: https://hal.inria.fr/hal-03105845.

[5] H. Malik, C. Adjih, C. Weidmann and M. Kieffer. 'MICN: a Network Coding Protocol for ICN with Multiple Distinct Interests per Generation'. In: *Computer Networks* 187 (2021), p. 107816. DOI: 10.1016/j.comnet.2021.107816. URL: https://hal.archives-ouvertes.fr/hal-02887550.

[6] L. Santos De Oliveira, P. Olmo Vaz de Melo and A. Carneiro Viana. 'Assessing Large-Scale Power Relations Among Locations From Mobility Data'. In: *ACM Transactions on Knowledge Discovery from Data (TKDD)* (2nd July 2021). URL: https://hal.inria.fr/hal-03277191.

[7] C. Y. Tazibt, N. Achir and T. Djamah. 'Online Drone-based Data Gathering Strategies for Ground Sensor Networks'. In: *International Journal of Sensor Networks* (2022). URL: https://hal.inria.fr/hal-03538548.

[8] D. Teixeira, J. Almeida and A. Carneiro Viana. 'On estimating the predictability of human mobility: the role of routine'. In: *EPJ Data Science* 10.1 (29th Sept. 2021). DOI: 10.1140/epjds/s13688-021-00304-8. URL: https://hal.inria.fr/hal-03360537.

[9] D. D. C. Teixeira, A. Carneiro Viana, J. M. Almeida and M. S. Alvim. 'Revealing challenges in human mobility predictability'. In: *ACM Transactions on Spatial Algorithms and Systems* (30th Apr. 2021). DOI: 10.1145/1122445.1122456. URL: https://hal.inria.fr/hal-03128639.

International peer-reviewed conferences

[10] 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.

[11] I. Ayoub, I. Hmedoush, C. Adjih, K. Khawam and S. Lahoud. 'Deep-IRSA: A Deep Reinforcement Learning Approach to Irregular Repetition Slotted ALOHA'. 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/PEMWN53042.2021.9664720. URL: https://hal.inria.fr/hal-03533523.

[12] R. Dagher, F.-X. Molina, A. Abadie, N. Mitton and E. Baccelli. 'An Open Experimental Platform for Ranging, Proximity and Contact Event Tracking using Ultra-Wide-Band and Bluetooth Low-Energy'. In: CNERT 2021 - IEEE INFOCOM Workshop on Computer and Networking Experimental Research using Testbeds. Virtual, France, 10th May 2021. URL: https://hal.inria.fr/hal-03140370.

[13] S. Faiz, N. Achir and K. Boussetta. 'Increasing vehicles perception using cooperative relaying and priority-based beaconing'. In: HPSR 2021 - IEEE 22nd International Conference on High Performance Switching and Routing. Paris, France: IEEE, 7th June 2021, pp. 1–6. DOI: 10.1109/HPSR52026.2021.9481799. URL: https://hal.archives-ouvertes.fr/hal-03534746.

[14] B. Greinke, G. Petri, P. Vierne, P. Biessmann, A. Börner, K. Schleiser, E. Baccelli, C. Krause, C. Verworner and F. Biessmann. 'An Interactive Garment for Orchestra Conducting: IoT-enabled Textile & Machine Learning to Direct Musical Performance'. In: TEI 2021 - 15th ACM International Conference on Tangible, Embedded and Embodied Interaction. Virtual, France, 14th Feb. 2021. DOI: 10.1145/3430524.3442451. URL: https://hal.inria.fr/hal-03138581.

[15] P. Jacquet and L. Tupikina. 'Geometry of Outdoor Virus Avoidance in Cities'. In: GSI 2021 - 5th International Conference on Geometric Science of Information. Geometric Science of Information. Paris, France, 21st July 2021, pp. 869–877. DOI: 10.1007/978-3-030-80209-7_93. URL: https://hal.archives-ouvertes.fr/hal-03532645.

[16] L. Jouans, A. Carneiro Viana, N. Achir and A. Fladenmuller. 'Associating the Randomized Bluetooth MAC Addresses of a Device'. In: CCNC 2021 - IEEE Consumer Communications & Networking Conference. Las Vegas, United States, 9th Jan. 2021. URL: https://hal.inria.fr/hal-03045555.

[17] A. Kumar Mishra, A. Carneiro Viana, N. Achir and C. Palamidessi. 'Public Wireless Packets Anonymously Hurt You'. In: *2021 IEEE 46th Conference on Local Computer Networks (LCN)*. IEEE LCN 2021 (Doctoral-track - Promising ideas). Edmonton / Virtual, Canada, 4th Oct. 2021. DOI: 10.1109/LCN52139.2021.9524956. URL: https://hal.archives-ouvertes.fr/hal-03298339.

[18] R. Lima Costa, A. Carneiro Viana, A. Ziviani and L. N. Sampaio. 'Tactful opportunistic forwarding: What human routines and cooperation can improve?' In: *Proceedings of the 35th International Conference on Advanced Information Networking and Applications (AINA-2021), Volume 3*. AINA2021 - 35th International Conference on Advanced Information Networking and Applications. Toronto, Canada, 12th May 2021. URL: https://hal.inria.fr/hal-03149909.

[19] A. K. Mishra, A. Carneiro Viana and N. Achir. 'SimBle: Comment générer des traces réelles Bluetooth conformes aux recommandations de préservation de la vie privée ?' In: ALGOTEL 2021 - 23èmes Rencontres Francophones sur les Aspects Algorithmiques des Télécommunications. La Rochelle, France, 2021. URL: https://hal.archives-ouvertes.fr/hal-03217312.

[20] D. Mvondo, M. Bacou, K. Nguetchouang, S. Pouget, J. Kouam, R. Lachaize, J. Hwang, T. Wood, D. Hagimont, N. de Palma, B. Batchakui and A. Tchana. 'OFC: an opportunistic caching system for FaaS platforms'. In: *EuroSys '21: Proceedings of the Sixteenth European Conference on Computer Systems*. EUROSYS 2021 - 16th European Conference on Computer Systems. Edinburgh (online), United Kingdom: Association for Computing Machinery (ACM), Apr. 2021, pp. 228–244. DOI: 10.1145/3447786.3456239. URL: https://hal.archives-ouvertes.fr/hal-03211416.

[21] 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.

Scientific books

[22] E. Baccelli. *Internet des Objets: Défis sociétaux et domaines de recherche scientifique pour l'Internet des Objets (IoT)*. 8th Dec. 2021. URL: https://hal.inria.fr/hal-03474906.

[23] E. Baccelli. *Internet of Things (IoT): Societal Challenges & Scientific Research Fields for IoT*. 8th Dec. 2021. URL: https://hal.inria.fr/hal-03474888.

Doctoral dissertations and habilitation theses

[24] L. Amichi. 'Understanding individuals' proclivity for novelty-seeking in human mobility'. Polytechnic School - IPP, 23rd Nov. 2021. URL: https://hal.inria.fr/tel-03537248.

[25] R. Costa. 'Tactful Networking as a Cornerstone for Opportunistic Human-Aware D2D Communication'. Institut Polytechnique de Paris; Universidade federal da Bahia, 3rd Aug. 2021. URL: https://tel.archives-ouvertes.fr/tel-03373800.

[26] D. Do couto teixeira. 'Predictability in Human Mobility : Interpretability, Extensions and Applications'. Institut Polytechnique de Paris; Universidade federal de Minas Gerais, 2nd Aug. 2021. URL: https://tel.archives-ouvertes.fr/tel-03376019.

Reports & preprints

[27] L. Amichi, A. Carneiro Viana, M. Crovella and A. Loureiro. *An inherent limiting factor of human mobility prediction*. INSTITUT POLYTECHNIQUE DE PARIS; INRIA Saclay, équipe Tribe, 3rd Feb. 2021. URL: https://hal.inria.fr/hal-03130267.

[28] 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.

[29] A. C. B L Monção, S. Luz Correa, A. Carneiro Viana and K. Vieira Cardoso. *Optimizing Content Caching and Recommendations with Context Information in Multi-Access Edge Computing*. INRIA Saclay - Ile de France (INRIA); Universidade Federal de Goiás, 30th Aug. 2021. URL: https://hal.inria.fr/hal-03329371.

[30] G. Banegas, K. Zandberg, A. Herrmann, E. Baccelli and B. Smith. *Quantum-Resistant Security for Software Updates on Low-power Networked Embedded Devices*. 10th June 2021. URL: https://hal.inria.fr/hal-03255844.

[31] S. L. Correa, K. V. Cardoso, F. F. Fonseca, L. Mamatas and A. C. Viana. *Itinerary Recommendation Algorithm in the Age of MEC*. Inria Saclay Ile de France, 2nd Feb. 2021. URL: https://hal.inria.fr/hal-03147515.

[32] L. S. De Oliveira, P. O. S. Vaz-De-Melo and A. Carneiro Viana. *Analysing locations power in large-scale mobility data*. 2nd Feb. 2021. DOI: 10.1145/1122445.1122456. URL: https://hal.inria.fr/hal-03128655.

[33] 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, 21st July 2021. URL: https://hal.inria.fr/hal-03219274.

[34] P. Jacquet and S. Janson. *Variations on depth-first search performance in random digraphs*. 20th Jan. 2022. URL: https://hal.archives-ouvertes.fr/hal-03537124.

[35] P. Jacquet, G. I. Shamir and W. Szpankowski. *Precise Minimax Regret for Logistic Regression*. 6th July 2021. URL: https://hal.archives-ouvertes.fr/hal-03279834.

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