RESEARCH CENTRE

Saclay - Île-de-France

2020 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

Keywords

Computer sciences and digital sciences

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1 Team members, visitors, external collaborators

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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 designing choices** involving its devices and related protocols/services as well as the edge-core network communication loop.

Toward this belief, the research of the team will be organized around three research directions: *(1) technologies for accomodating low-end IoT devices; (2) technologies for leveraging high-end IoT devices' advents; and (3) technologies for edge-core network interaction.* With those three research directions, the team places its efforts in the three main elements composing the ecosystem of IoT devices: (1) the device itself, (2) their usability, and (3) their network context.

More specifically, the first element tackles the optimization, simplicity, and unification requirements imposed by the heterogeneity and low capabilities of low-end IoT devices. This brings the necessity to deal with hardware and software specificity of devices, while adapting designing choices and simplifying deployment. The second element focus on issues related to "how" and "for what" IoT devices are used. This also brings the human element into play, which dynamics are shaping the way their mobile devices are interacting with the edge of the Internet and consequently, are requesting and consuming network resources and services. Finally, the third element closes the *network→usability→device→network* loop by bringing solutions supporting functions and communication between IoT devices and the core of the Internet.

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.

- **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.

- **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.

- **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

- Computer science, Wireless networks, Internet of Things, Intelligent network and cities, Human mobility analytics and predictability, Resource allocation and mangement, IoT software design, Social network, Energy saving.

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 and urbanization investigation** (e.g., in the successful comprehension of the spread of epidemics or of the population; in urban planning and transportation management; in intelligent transportation systems in smart cities; or for urban space management). The SafeCityMap 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

6.1 Awards

Together with their co-authors, Iman Hmedoush and Cédric Adjih were awarded the **best paper award** at the PEMWN 2020 Conference, December 2020, for the article on **Multi-Power Irregular Repetition Slotted ALOHA inHeterogeneous IoT networks** [22] (collaboration with P. Mühlethaler and Lou Salaün).

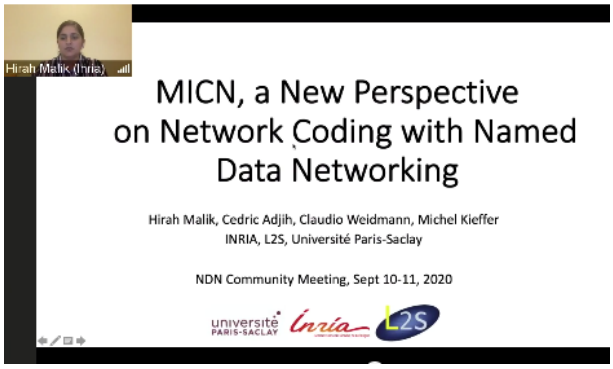
Philippe Jacquet has been elevated to **IEEE Fellow** on January 2020 for **contributions to wireless protocols and communication networks**.

6.2 RIOT: Summit & Releases 2020

This year, we organized the RIOT Summit conference (link to the website) gathering 170+ participants coming from 4 continents, and delivering

high-quality speakers, including a keynote from operating system research domain star Andrew S. Tanenbaum. In 2020, teaming up with other RIOT contributors, we published four official RIOT releases (release 2020.01, release 2020.04, release 2020.07, release 2020.10) merging 2000+ pull-requests from dozens of contributors worldwide throughout 2020, overall passing the mark of 33k commits to the master branch of RIOT.

6.3 Network Coding and Information Centric Networking



Hirah Malik presented our new protocol MICN combining Network Coding and Information Centric Networking, at the NDN Community Meeting 2020, September 10 - 11, 2020 (link to video).

7 New 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

Contacts: Vincent Roca, Cédric Adjih

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

Contacts: Abhishek Mishra, Aline Carneiro Viana, Nadjib Achir

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

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

Partner: ENS Lyon

7.2 New platforms

Open Experimental IoT Platforms

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 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. Such results were published at a paper at IEEE Globecom 2017.

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. Our mechanism can serve as a standalone application for adaptive location sampling, or as a complementary tool alongside auxiliary sensors (such as accelerometer and gyroscope). In this work, we implemented our mechanism as an application for mobile devices and tested it on mobile users worldwide. The results from our preliminary experiments show that our method adjusts the sampling frequency to the mobility habits of the tracked users, it reliably tracks a mobile user incurring acceptable approximation errors and significantly reduces the energy consumption of the mobile device. Such results are in-submission to the IEEE Trans. on Mobile Computing (TMC) journal and also registered at Hal Inria as the Research Report [44].

This is an on-going work with 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 and has started a PhD in co-tutelle with Aline C. Viana and Javier Bustos (NIC/Univ. of Chile).

8.2 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)*.

According to Cisco forecasts, mobile data traffic will grow at a compound annual growth rate of 47 % from 2016 to 2021 with smartphones surpassing four-fifths of mobile data traffic. 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, Offloading Regions (ORs) are identified and characterized from individual GPS trajectories when small offloading time windows are considered. The characterization is performed in terms availability, sojourn, transition time; type and spatial characteristics. We then evaluate the offloading opportunities provided to users while they are travelling in terms of availability, time window to offload, and offloading delay. The results show that (i) attending to users mobility, ten seconds is the minimum offloading time win- dow 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). Next we extended the above work as following.

Offloading Regions (ORs) are extracted from two different mobility traces datasets and offloading opportunities are analyzed. We study the mobility predictability in an offloading scenario through the theoretical and practical evaluation of several mobility predictors. Our detailed evaluation shows that mobility predictability in an offloading scenario is far more challenging than mobility between PoIs due to the new ORs phenomenon. Here, ML predictors outperform common MC predictors used in the literature by at least 15% depending on the offload time threshold considered, revealing the importance of context information in an offloading scenario. An extensive analysis shows a predictive performance improvement up to ≈ 35% if mobility regularity properties are considered. Finally, we discuss the properties that characterize human mobility for offloading, namely *the exploration phase, the mobility regularity, and offloading locations*, as well as their impact on the design of offloading systems. Specifically, we have clearly identified that considering longer learning periods for offloading systems will not improve their capacity of predicting mobility. However, mobility regularity can be leveraged to improve predictability by ≈ 27% at the expense of fewer offloading opportunities and therefore, both opportunistic and deterministic strategies should be supported by offloading systems. Attending to the characteristics of offloading locations from both datasets, we show that in the majority of the cases, APs already deployed in urban environments can provide full coverage to users while offloading, decreasing the need for handovers. Indeed, offloading mobility indicates that mobile devices do not need to perform multiple handovers during the offloading process as offloading sites can be covered by a small number of APs. Finally, conclusions and findings regarding the offloading mobility properties studied in this work are shown to be valid for different urban scenarios given the high degree of similarity between the results from two different mobility datasets.

This last extended work is under submission at the IEEE Trans. on Mobile Computing (TMC) journal, and also registered at Hal Inria as the Research Report (hal-03128649). This is an on-going work with the the PhD Emanuel Lima (one of my co-supervision), who spent 4 months as an intern in our previous team in 2018, and his advisors.

8.3 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. In a different approach, other works address the human mobility in terms of social influence which refers to the case when individuals change their behaviors persuaded by others. Nevertheless, fewer works measure influence of POI based on human mobility data.

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. Key location identification in cities is a central in human mobility investigation as well as for societal problem comprehension. 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). Different from literature, we consider the flow of people in our analysis, instead of the number of neighbor PoIs or their structural locations in the city. Thus, 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. The attract power and support power measure how many visits a PoI gather from and disseminate over its neighborhood, respectively. Moreover, the independence power

captures the capacity of PoI to receive visitors independently from other PoIs. We tested our methodology on well-known University Campus mobility datasets and validated on Location-Based Social Networks (LBSNs) datasets from various cities around the world. 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 published in ACM MobiWac [52]. An extended version is under-review (2nd round, major review) at the ACM Transactions on Knowledge Discovery from Data (TKDD) journal and also registered at Hal Inria as the Research Report [40]. Lucas did an internship in our team from Nov. 2019 to Jan. 2020.

8.4 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)*.

The next generation of mobile phone networks (5G) will have to deal with spectrum bottleneck and other major challenges to serve more users with high-demanding requirements. 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. Nowadays, mobile devices are attached to human daily life activities, and therefore communication architectures using context and human behavior information are promising for the future. 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. Hence, these solutions tend to only consider user features that can be measured from the network point of view, ignoring the ones that are intrinsic from human activity (e.g., daily routines, personality traits, etc).

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. Finally, we outline challenges and opportunities for future research. This tutorial paper was published at the IEEE Transaction on Emerging Topics in Computational Intelligence in 2020 [10].

Then, we first 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. We report the experience through a case study with a real-world dataset along with results from trace and metrics analysis. 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) [27].

Still, related literature typically considers users encounters and individual mobility, points of interest (PoIs), and time-evolving social ties between node pairs. Apart from that, not much was done to approximate the evaluation metrics to broader inherent aspects of human mobility while targeting QoE and QoS. There is thus 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. We compare TOOTS with the most popular state-of-art social-aware algorithm, Bubble Rap, combined with three dissemination policies. Results from TOOTS show increased performance in terms of delivery rate, delivery latency, and overhead. In particular, 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 and an extended version is in-writing to be submitted to a journal.

8.5 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)*.

Human mobility has been studied from different perspectives. One approach studying human mobility addresses predictability, i.e., deriving theoretical limits on the accuracy that any prediction model can achieve in a given dataset. Measuring the predictability of human mobility is, however, 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 plan to establish the theoretical foundations for the computation of interpretable and extensible predictability of mobility. We revisit the state-of-the-art method for estimating the predictability of a person's 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. We show that these two simple measures 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. We are the first to quantify the impact of different types of contextual information on predictability in human mobility, for different prediction tasks and datasets. 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. Specifically, we conduct a more detailed evaluation of the relationship between regularity, stationarity and entropy estimates for *both* next-cell and next-place prediction. We show that these two simple metrics are complementary and, when used jointly, are able to explain most of the variation in the main state-of-the-art predictability approach. As such, we use them as proxies of that technique to analyze how the predictability of one's mobility varies. Second, 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, the benefits of introducing context into the main state-of-the-art entropy estimator strongly depends on other factors such as the size, regularity and stationarity of the input sequence. Indeed, we found that in several cases, the original estimator, without context, remains the best approach, producing lower entropy values (higher predictability). These results hint at the observation that using context may not always bring benefits to predictability estimate in practical scenarios. This work extension is under submission to the ACM Transactions on Spatial Algorithms and Systems (TSAS) journal, 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, reference hal-03128639 [49].

Going forward, we propose to view human mobility as consisting of two components, routine and novelty, with distinct properties. This alternative view of one's mobility allows us to identify unpredictable behavior in each of these components. Additionally, we argue that unpredictable behavior in the novelty component is hard to predict, and we then focus on analyzing what affects the predictability of one's routine. To that end, 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. Finally, we rely on previously proposed metrics (i.e., *regularity* and *stationarity*), as well as a newly proposed one, to understand what affects the predictability of a person's routine. Our experiments show that our metrics are able to capture most of the variability in one's routine, and 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 is under submission to the EPJ Data Science journal. A related report can be found in Hal Inria, reference hal-03128624 [48].

8.6 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)*.

The prediction of individuals' dynamics has attracted significant community attention and has implication for many fields: e.g. epidemic spreading, urban planning, recommendation systems. Current prediction models, however, 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.

Many prediction models have been proposed to forecast individuals trajectories. However, they all show limited bounded predictive performance. Regardless of the applied methods (e.g., Markov chains, Naive Bayes, neural networks), the type of prediction (i.e., next-cell or next place) or the used data sets (e.g., GPS, CDR, surveys), accuracy of prediction never reaches the coveted 100%. The reasons for such limitations in the accuracy are manyfold: the lack of ground truth data, human beings' complex nature and behavior, as well the exploration phenomenon (i.e., visits to never seen before places).

We focus on such phenomenon, which has rarely been tackled in the literature but indeed, represents a real issue: Previous studies either did not provide any consideration of the exploration factors of individuals, or divided the population-based on properties that are not always consistent, or assumed that all individuals have the same propensity to explore. 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). Further, we extract and analyze the mobility traits specific to each profile. We then investigate temporal and spatial patterns in each mobility profile and show the presence of recurrent visiting

behavior of individuals even in their novelty-seeking moments. Our results unveil important novelty preferences of people, which are ignored by literature prediction models. Finally, we show that prediction accuracy is dramatically affected by exploration moments of individuals. We then discuss how our profiling methodology could be leveraged to improve prediction. individuals according to their degree of exploration: scouters, routiners, and regulars.

This work was published at the Student workshop of ACM CONEXT 2019 and in the French Algotel conference 2020 [33]. An extended version was then published at the ACM SigSpatial 2020 [15]. A journal is in-writing to be submitted to the IEEE Transactions on Network Science and Engineering where we evaluate the impacts of novelty-seeking, quality of the data, and the prediction task formulation on the theoretical and practical predictability extents. A technical report on this last work is available at Hal Inria [37].

8.7 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 under submission at the IEEE Communication and Tutorial Surveys journal and a technical report can be found at Hal Inria under the reference: hal-03105845 [45].

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

8.8 Minimal Virtual Machines on IoT Microcontrollers

Participants Koen Zandberg, Emmanuel Baccelli.

Virtual machines (VM) are widely used to host and isolate software modules. However, extremely small memory and low-energy budgets have so far prevented wide use of VMs on typical microcontroller-based IoT devices. In this work, we explore the potential of two minimal VM approaches on such low-power hardware. We design rBPF, a register-based VM based on extended Berkeley Packet Filters (eBPF). We compare it with a stack-based VM based on We-bAssembly (Wasm) adapted for embedded systems. We implement prototypes of each VM, hosted in the IoT operating system RIOT. We perform measurements on commercial off-the-shelf IoT hardware. Unsurprisingly, we observe that both Wasm and rBPF virtual machines yield execution time and memory overhead, compared to not using a VM. We show however

that this execution time overhead is tolerable for low-throughput, low-energy IoT devices. We further show that, while using a VM based on Wasm entails doubling the memory budget for a simple networked IoT application using a 6LoWPAN/CoAP stack, using a VM based on rBPF requires only negligible memory overhead (less than 10 percent more memory). rBPF is thus a promising approach to host small software modules, isolated from OS software, and updatable on-demand, over low-power networks.

This paper was published in PEMWN 2020 [32].

8.9 Standardization of General-Purpose Secure Software Updates for IoT Devices

Participants Koen Zandberg, Emmanuel Baccelli.

TRiBE co-authors the new IETF standard (work-in-progress) providing low-end IoT devices with secure software updates. The Internet Draft **draft-ietf-suit-manifest-04** 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 `https://tools.ietf.org/html/draft-ietf-suit-manifest-04`.

8.10 Deep Learning for Constrained Devices (TinyML and Edge AI)

Participants Matthieu Chatard *(student,TSP)*, Hyun-Chul Choi *(student,TSP)*, Nimesh Tahalooa *(student,TSP)*, Cédric Adjih, Anis Laouiti *(TSP)*, Alexandre Abadie, Nadjib Achir, Emmanuel Baccelli.

This year, with students of Telecom SudParis, we started experimenting with Deep Learning for microcontrollers (such as Arduino 33 BLE): training neural networks for keyword recognition. We also experimented with Edge AI on constrainted Linux devices (such as the Nvidia Jetson), with an example application of "fire detection", based on transfert learning.

8.11 Modern Protocols: Information Centric Networking and Network Coding

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 started with an analysis of the properties of a major (section 8.11.1). A breakthrough was the defintion of our protocol MICN (MILIC-ICN), a highly efficient ICN and Network Coding protocol (section 8.11.2); this protocol is based on a mathematical consrtuction on sets, denoted MILIC (Multiple Interests for

Linearly Independent Contents). MILIC is a family of solutions of the mathematical problem of "Sets Ensuring Linearly Independent Transversals" (SELIT); we have proven that it is the only solution for a large class of solutions (section 8.11.3).

8.11.1 Analysis of the properties of NetcodICN protocols

Information Centric Networking (ICN) is a family of recent protocols based on a paradigm different from traditional IP networks. A natural and well-adapted extension to this type of networks is the use of network coding: this has been exploited in the previously proposed family of NetcodCCN/NetcodNDN protocols, which are capable of reaching network capacity. However, this has been observed with heuristics, and on a few examples of networks. We analyze more formally the properties of several variants of the protocol.

This work as been published at CoReS'2020 [29].

8.11.2 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 on 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 [14].

8.11.3 On the Problem of Finding "Sets Ensuring Linearly Independent Transversals" (SELIT), and its Application to Network Coding

This paper introduces a new formal mathematical problem initially motivated by an application of Network Coding (NC) to Information Centric Networks (ICN). It is of more limited scope but is remotely inspired by the well-known index coding problem. It is presented as follows: "given a vector space, can one construct several subsets of vectors, such that when drawing arbitrarily one vector from each subset, the selected vectors would be always linearly independent?". Answering this question is a step to construct an ICN efficient scheme with NC. We prove that our previously introduced construction is the only possible solution for a large family of constructions. This is an important result by itself. It also implies that any alternate solutions are outside this family and we propose one example.

This work as been published at PEMWN 2020 [30].

8.12 Wireless Random Access Protocols: Physical and MAC Layer Design for Active Signaling Schemes in Vehicular Networks

Participants Fouzi Boukhalfa *(Inria, EVA)*, Cédric Adjih, Paul Mühlethaler *(Inria, EVA)*, Mohamed Hadded *(VeDeCm)*, Oyunchimeg Shagdar *(VeDeCom)*.

Nowadays, many telecommunication systems (wifi, cable systems and 4G, 5G cellular networks) use Orthogonal Frequency Division Multiplexing (OFDM) as the physical layer standard. The design of efficient OFDM signal detection algorithms is very important to provide reliable systems, and this is particularly true for Vehicular Adhoc Networks (VANETs) involving autonomous vehicles, where missing

a signal or detecting a fake one may cause a dangerous situation. The performance of these algorithms is generally evaluated in terms of their robustness against noise. In this work, we evaluate the probability of error in signal detection in order to establish the minimum length of preamble needed for the active signaling process. This mechanism is used in AS-DTMAC (active signaling fully distributed TDMA-based MAC protocol) to reduce access collisions. Thus, by reducing the length of the preamble, greater time is given for the payload part of the packet, resulting in increased throughput.

This paper was published at WiMob 2020 [16].

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

Participants Iman Hmedoush, Cédric Adjih, Paul Mühlethaler, Chung She Chen *(Nokia Bell Labs)*, Lou Salaun *(Nokia Bell Labs)*, Vinod Kumar *(WWRF)*.

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 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 three aspects or variant of IRSA: first we revisited the variant with multiple packet reception (MPR); then we studied Multi-Power IRSA where transmission powers can be different among nodes (but each node keeps same transmission power); finally we applied machine-learning techniques to IRSA.

8.13.1 On the Performance of Irregular Repetition Slotted Aloha with Multiple Packet Reception

Additionally, IRSA had previously been studied for many different variants and settings, including the case where the receiver is equipped with "multiple-packet reception" (MPR) capability. In this article, we extensively revisit the case of IRSA with MPR. First, one of our major results is the proof that K-IRSA cannot reach the natural bound of throughput, and we prove a new, lower bound for its performance. Second, we give a simple expression for its excellent loss rate at lower loads. Third, we show how to formulate the search for the appropriate parameters of IRSA as an optimization problem, and how to solve it efficiently. By doing that for a comprehensive set of parameters, and by providing this work with simulations, we give numerical results that shed light on the performance of IRSA with MPR.

This article was presented and published at IWCNC 2020 [21].

8.13.2 Multi-Power Irregular Repetition Slotted ALOHA in Heterogeneous IoT networks

Motivated by multiple previous studies of IRSA performance in different settings, we focus on the scenario of an IoT network where the packets of different nodes are received with different powers at the base station, either per design due to different transmission power, or induced by the fact that the nodes are at different distances from the base station. In such a scenario, the capture effect emerges at the receiver, which in turn enhances the protocol performance. We analyze the protocol behavior using a new density evolution which is based on dividing nodes into classes with different powers. By computing the probability to decode a packet in the presence of the interference, we explore the achievable throughput and its associated gain and show the excellent performance of Multi-Power IRSA.

This article was published in PEMWN'2020 [22] and obtained the best paper award.

8.13.3 A Regret Minimization Approach to Frameless Irregular Repetition Slotted Aloha: IRSA-RM

See section 8.14

8.14 Machine Learning for Network Protocols

Participants Iman Hmedoush, Cédric Adjih, Paul Mühlethaler, Hassan Fawaz *(UVSQ)*, Kinda Khawam *(UVSQ)*, Samer Lahoud *(ESIB)*, Steven Martin *(LRI, Université Paris-Saclay)*.

8.14.1 A Regret Minimization Approach to Frameless Irregular Repetition Slotted Aloha: IRSA-RM

This article studies one of these modern random access protocols: Irregular Repetition Slotted Aloha (IRSA). Since optimizing its parameters is not an easily solved problem, in this article we use a reinforcement learning approach for that purpose. We adopt one specific variant of reinforcement learning, Regret Minimization, to learn the protocol parameters. We explain why it is selected, how to apply it to our problem with centralized learning, and finally, we provide both simulation results and insights into the learning process. The results obtained show the excellent performance of IRSA when it is optimized with Regret Minimization.

This article has been published in MLN'2020 [34].

8.14.2 Joint Spreading Factor and Channel Assignment in Multi-Operator LoRaWAN Deployments

LoRaWAN is a popular internet of things (IoT) solution over the unlicensed radio band. It sustains low-cost, durable, and long range IoT wireless communications. Nonetheless, with over 24 billion connected IoT devices being expected by the end of the year, and over 50 billion by 2025, the concurrent and legacy approaches to spreading factor and channel assignment in LoRaWAN networks can no longer keep up. This is exacerbated with the growing densification of IoT device deployments and, with the increasing requirements for better throughput and packet delivery ratios. In this work, we propose a proportional fair-based joint optimal formulation for spreading factor and channel assignment in multi-operator LoRaWAN deployments. The objective of this problem is to maximize the total sum of the logarithmic normalized throughput. We split the problem into two subproblems, and propose a game theoretic approach to solving them. We prove that our games converge towards a pure Nash equilibrium and, afterwards, solve the optimization problems using both semi-distributed and completely distributed algorithms. Via simulations, we show that our algorithms greatly improve the total normalized throughput for LoRaWAN as well as the packet success rate, in comparison to the legacy approaches.

This article has been published in: Hassan Fawaz, Kinda Khawam, Samer Lahoud, Cédric Adjih, Steven Martin. "Joint spreading factor and channel assignment in multi-operator lorawan deployments". Sensors, MDPI, 2021, 21 (1), pp.1-19, [3].

8.15 Blockchain moderated by empty blocks to reduce the energetic impact of crypto-moneys.

Participants Philippe Jacquet *(Inria)*, Bernard Mans *(Macqarie U)*.

There are three main sources of energy consumption in IT: the data centers, the bitcoin mining, the deep neural networks training. One could consider that among the three sources of waste the bitcoin mining is the less useful. Recent estimates evaluate bitcoin mining CPU to the equivalent of the power consumption of a country like Greece.

While cryptocurrencies and blockchain applications continue to gain popularity, their energy cost is evidently becoming unsustainable. In most instances, the main cost comes from the required amount of energy for the Proof-of-Work, and this cost is inherent to the design. In addition, useless costs

from discarded work (e.g., the so-called Forks) and lack of scalability (in number of users and in rapid transactions) limit their practical effectiveness.

The green mining proposed in our result [12] is an innovative scheme which eliminates the burden of the Proof-of-Work. We prove that our scheme guarantees a tunable and bounded average number of simultaneous mining whatever the size of the population in competition, thus by making the use of nonce-based techniques unnecessary, achieves scalability without the cost of consuming a large volume of energy. The technique used in the proof of our scheme is based on the analogy of the analysis of a green leader election.

The new scheme opens the possibility of high frequency blockchains, where certification of extremely frequent updates inside the IoT network can be obtained via scalable green mining. This opens the perspective of monitoring and simulating large portion of the world via sensor via a digital twin world.

8.16 An innovative modeling of city geometry and urban wireless networks via Hyperfractals.

Participants Philippe Jacquet *(Inria)*, Bernard Mans *(Macqarie U)*, Dalia Popescu *(Nokia)*, Bartek Blaszczyszyn *(Inria)*.

The goal of this topic is to increase our understanding of the fundamental performance limits of urban vehicle networks by exploiting the self-similarity and hierarchical organization of modern cities. We use an innovative model called "hyperfractal" that captures the self-similarity of the topology and vehicle locations while avoiding the extremes of regularity and randomness.

A hyperfractal measure shows self similar patterns that reveal a fractal dimension d_F which is larger than the dimension of the embedded space (2). This kind of measure is particularly well suitable to model a urban street map. Map fitting show hyperfractal dimemsion of order $3-4$ for random cities in US or Europe.

We prove that the transport capacity in a hyperfractal increases in $n^{1-1/(d_F+1)}$ when the number of mobile n increases. This must be compared to the generalized result of Gupta and Kumar which tells that the transport capacity of a wireless multi-hop network embedded in an euclidian space of dimension D is in $n^{1-1/D}$. In other words, a hyperfractal city behaves like a hypercube of dimension d_F+1.

We also evaluate the performance in terms of energy consumed in end-to-end communication. We show [47] that the trade-off between delays of end-to-end transmission and end-to-end consumed energy. We prove that the transmission delay for an end-to-end transmission increases in $n^{1-\alpha/(d_F-1)}$ for a global energy cost in $n^{-\delta(1-\alpha)}$ where δ is the radio attenuation factor in the streets. This proves that for both constraints the energy decreases as we allow choosing delays to increases. The asymptotic limit of the energy becomes significantly small in theory when the number of nodes becomes asymptotically large.

In a second result [36] we investigate how a hybrid system of base stations and flying drones can help to cover a whole city under 5G. With a main purpose to extend connectivity and guarantee data rates, the drones require an intelligent choice of hovering locations due to their specific limitations such as flight time and coverage surface.

Namely, we prove that assuming n mobile nodes (distributed according to a hyperfractal distribution of dimension d_F) and an average of n^θ Next Generation NodeB (gNBs), distributed like an hyperfractal of dimension d_r with $\theta > d_r/4$ and letting n tending to infinity (to reflect megalopolis cities), then the average fraction of mobile nodes not covered by a gNB tends to zero like $O\left(n^{-\frac{(d_F-2)}{d_r}(2\theta-\frac{d_r}{2})}\right)$. Interestingly, we then prove that the average number of drones, needed to connect each mobile node not covered by gNBs is comparable to the number of isolated mobile nodes. We complete the characterisation by proving that when $\theta < d_r/4$ the proportion of covered mobile nodes tends to zero.

8.17 Ariane Covid, application for limited virus exposure in outdoor excursion.

Participants Philippe Jacquet *(Inria)*, Cedric Adjih *(Inria)*, Liubov Tupikana *(Nokia)*.

The main issue in fighting a pandemic virus propagation is the limitation and reduction of contact between susceptible people and infected people, in particular during lock-down period. Lockdown periods have been set in most part of the planet in order to limit the contacts between people in the ignorance of their status (infected, susceptible, immunized).

The aim of the first result described in the Hal's research report [jacquet:hal-02546347] is to recommend safe outdoor path inside cities in order to limit the exposure to virus propagation. The main idea is to make a load balancing between streets via space-time diversity. The application is shown to be efficient at the very first user, and lead to an optimal Nash equilibrium when there is a majority of user. We have tried a performance analysis over prior lock-down pedestrian traffic estimates over Paris, Manhattan and Rome. It is shown that application reduces the user exposure cumulative time by a factor three.

The aim of the second result [41, 43] is about the situation after lock-down where outdoor excursions have again a aim beyond promenade, mostly in commuting to work or shopping beyond direct vicinity. In particular we investigate the biking path optimization. We use drifted random walks for establishing path. We want that under the condition of uniformity of the path end points, the resulting street occupancy gives a perfect or quasi perfect load balancing. We compare this with the case when biking lanes are just following the main commuting lanes by bus or subway, thus minimizing the exposure to virus by a factor between 3 and 9 on various models. Interestingly the path selection is immediately beneficial to the first user even if the other users stay on preferential paths.

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

Participants Aline Carneiro Viana, Artur Ziviani *(LNCC)*, Haron Calegari Fanteceli *(LNCC,Inria)*, Razvan Stanica *(Inria)*, Solohaja Rabenjamina *(Inria)*.

In SafeCityMap, we argue that the study and modelling of people's mobility and activity patterns can provide a clear association with epidemic spread, such as COVID-19, in areas of a city.

In the first phase of SafeCityMap, we perform a data-driven mobility analysis on large-scale datasets collected in Ile de France region, and more particularly, in Paris departments. Our goal is to quantify (in space and time): (1) the attendance of and (2) the visiting flows in different urban areas, both before and during the 1st lockdown, so as to quantify the consequences of mobility restrictions and decisions at a urban scale.

In general terms, we identify the zones in a city having an important participation on the daily routine of people according to their habits of movements and visits. Indeed, some strategically positioned zones are likely to be more popular, to attract and/or to disseminate more people to neighbors areas. Finally, we measure the risk of each zone by combining results of their importance, namely *risk factor*.

We claim the assigned zone's risk factor is directly correlated to the spatiotemporal risk of a disease contamination and propagation in that zone. In other words, high population concentration at certain hours and geographical area intuitively increases the probability of agglomeration and consequently, the contamination and propagation risks. A report with the corresponding outputs is in-writing and apresentation of the general results was presented by A. C. Viana at "Unithé ou Café" at Inria Saclay (Jan. 2021).

In a second phase, we plan to assess the impact of these mobility restrictions on the epidemic spread of COVID-19 among the population and make available a web tool allowing the easy visualization of the risk factor evolution in time.

Societal Impact: Such information can then feed other applications (eg, ArianeCovid, ie, spots to avoid in a journey) as well as draw the authorities attention to particular areas. Our methodology also makes it possible to identify transit zones common to several zones of activity. Special attention should be paid to these areas, with a real potential for the virus to spread between communities. On the basis of our results, public policies could be put in place to better separate the different areas of activity.

Finally, risk factors evolution attributed to the territories by day or by week could be followed, which will provide support to the public authorities in the choice of policies to be put in place. In other words,

our studies will tell the authorities if a correlation between the rates of visits to a territory and the spread of the epidemic exists, and why (type of territory, position, time slots)?

8.19 Social network structure and trends, modeling and tracking.

Participants Philippe Jacquet *(Inria)*, Wojciech Szpankowski *(Purdue U)*, Dimitrios Milioris *(Nokia)*, Krzysztof Tuperski *(Jagelonian U)*.

In this section we investigate the activities which consists into extracting information from social networks in order to predict the dynamic of the communication network. For example an event external to the network, for example a gathering of people for a sport event, may create an important load. If this event can be predicted well in advance via social network monitoring, the operator will have time to move extra resources to the hot spots.

We have developed a technique, called *joint complexity* backed by Information Theory, which allow to track main trends just by comparing the joint information of the text. We just compute the number common factors between the two texts. A common factor is a sequence of consecutive symbols which are common to both texts (we can call then N-grams). The larger the number of common factor is, the closer the topics are assumed. The joint complexity defines thus a distance between texts from which we can infer cluster of trends.

The evaluation of the joint complexity is obtained via suffix trees and is therefore linear in the length of the texts. The joint complexity is particularly well adapted for short text as those we find in Twitter. It is extremely robust since it accepts high variation in grammar and semantics and does not need any training. The method has been extensively used to track news in Twitter.

Interestingly the performance of joint complexity is tractable in information theory for various source models models. When the texts are identical, the average joint complexity is $n^2/2 + O(n)$ where n is the length of the text. When the text are different the average joint complexity is $O(n^\tau)$ where $\tau \leq 1$ is a solution of a Dirichlet equation, $\tau = 1$ corresponds to the case when the sources are independent but share the same statistics. We have proven this result in memoryless sources. Recently [13] we have extended these result to the most realistic case where the sources are markovian of finite memory. The later is much more realistic when dealing with natural texts.

In a second result presented in the conference *Analysis of Algorithms* [35], we have extracted more refined results about the pattern matching over Markovian text, in particular the redundancy of the complexity in a single text over the entropy. This second term quest remained an open problem since the invention of the Lempel-Ziv compression algorithms in 1977 and 1978. It is an important parameter since social media deals with short text where the redundancy might be of the same order than the entropy.

In a third problem, published at AofA2020 [jacquet:hal-03123680] we attack the models of the formation of user clusters of affinity. We take an alternative model of the preferential attachment model which is the duplication graph model invented by Bhan. In this model a new arrived user randomly select a neighbor and some of the neighbors of this neighbor, *i.e.* create its own sub-cluster by partial duplication of the cluster of its new neighbor. This model is more realistic to model the growth of a social network. We prove that the distribution of the degrees in each cluster has a power law tail which is confirmed by the statistics collected over the social networks. The methodology is based on multi-dimensional Mellin transform over Dirichlet generating functions.

8.20 Machine Learning and Artificial Intelligence, limits of learnability.

Participants Philippe Jacquet *(Inria)*, Wojciech Szpankowski *(Purdue U)*, Gil Shamir *(Google Inc)*.

In online learning sequentially received data must be used to update the predictor for subsequent data. In a supervised online setup, a model is trained to learn parameters from examples/ samples whose outcomes are already labeled. The training algorithm consumes data in rounds, where at each round

$t \in \{1, 2, ..., T\}$, it is allowed to predict the label based only on the labels it observed in the past $t-1$ rounds. The prediction algorithm incurs for each round some loss and updates its belief of the model parameters. In this work, we study a more specific setting of online logistic regression for binary classification. Logistic regression has recently received a lot of attention in machine learning since it connects information theory to machine learning.

In our result [42] we phrase our learning problem in terms of a game between nature/ environment and a learner. At each round the learner obtains a d dimensional training feature vector x_t and makes prediction y_t . Then we compare with the true label. The difference is the *loss*. We want to evaluate the cumulated loss, called the regret, as a function of T. More precisely, we want to establish an incompressible *minimax* lower bound to the regret. We show that this bound that in linear regression, is $\frac{d}{2}\log T + C_d + O(d^{3/2}/\sqrt{T})$ where C_d is exactly determined by an indefinite explicit integral in dimension d. This result gives an insight in the learnability limit of Artificial Intelligence.

We have presented some of our preliminary reflection about learnability in a workshop common with Nokia given and l'Institut des Hautes Etudes Scientifiques in Paris.

8.21 Privacy failure in Bluetooth MAC address randomization

Participants Loïc Jouans, Abhishek Kumar Mishra, Aline Carneiro Viana, Nadjib Achir, Anne Fladenmuller *(Sorbonne University)*.

Bluetooth devices naturally emit many public signals. It opens new paths for passive mobility analysis and allows building larger datasets direly needed by the research on mobile systems and raises new practical challenges. One of them is the correlation between the public packets and the emitters. The Bluetooth standard forces devices change the identifier they (i.e., MAC address) embed within the public packets regularly. In this work, we focus specifically on the MAC randomization process, and we show that it does not prevent packet correlation and device identification. We introduce an association strategy that leverages the low frequency of MAC changing at our advantage to associate different MACs from the same device. For this, we rely on a weak identifier–the timing between advertising packets–and weigh the tentative associations with the distance between their weak identifiers. We tested our strategy on a small but controlled dataset; as the algorithm benefits from a low number of devices, we applied it on two more significant stress tests. In these cases, as it is close to impossible to get a ground truth, we used markers hinting at the method success.

Compared to the literature, existing works target specific types of devices or OS versions; they reduce the device identification and the size of a mobility dataset. Instead, our approach targets any Bluetooth signal devices publicly emit. To the best of our knowledge, we are the first to bring a solution to associate Bluetooth randomized MAC addresses together, denoted as an **association strategy.** Such an approach will allow the scientific community to study device mobility despite the Bluetooth MAC randomization process.

This work is related to ANR MITIK (2020-) and has been published in CCNC 2021 [24]. An extended version of this work is currently an ongoing paper. In this extension, we use simulation to generate large-scale BLE traces with varying test conditions and associated *ground truth*. These traces are used in the evaluation. For 40 devices in the sniffing zone of a sniffer, we achieve an accuracy of close to 100%. The proposed approach performed very well in the highly-dense and mobile scenarios and gave a minimum of 83% accuracy. In terms of performance, the size of conflict clusters is always well below our stated bounds, making the associations possible in seconds.

8.22 Generating privacy preserving real-world BLE traces

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. 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 work, 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 [24]. 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. Finally, we provide privacy recommendations based on our case study.

This work is related to ANR MITIK (2020-) and a preprint work is availalbe at HAL-inria at the reference [46].

8.23 On the benefits of increased vehicles perception to cooperative communications: a performance evaluation study

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

Intelligent Transportation Systems (ITS) are expected to play a vital role in increasing road safety and road efficiency in the near future. ITS applications' primary feature is to provide road safety, which is based on IEEE-802.11p technology, by transmitting safety messages to the vehicles in the surrounding. The channel congestion is a significant challenge for the IEEE802.11p, ITS is operating on. Congestion increases the data loss and degrades the ITS performance resulting from compromising passengers' safety. In this work, we analyze the benefits of exploiting vehicle's embedded sensors to enhance car perception and improve the efficiency of cooperative communications. To this purpose, we implemented the collaborative environment perception approach for vehicular safety applications presented in one of our previous works and deeply analyze its performance and behavior in congested urban traffic. We extensively evaluate the ECAM (Extended Cooperative Awareness Message) protocol in this work. Using ECAM, vehicles collect the surrounding vehicles' status information in their detection range, thanks to embedded sensors (cameras, radars, lidars, etc.), and share this information through a collaborative beaconing scheme to reduce congestion in the communication channel. This scheme implements a dual step mechanism to function. The first phase implements the cooperative perception mechanism by adding the locally collected information in the safety message and sharing it to intensify the awareness among the vehicles in its communication surrounding. In the second phase, the recipient vehicles verify the accuracy of the information received from the collective perception enabled vehicles by leveraging the position by adding an error threshold. Performance evaluation conducted through extensive simulations shows the benefits of exploiting increased perception to enhance awareness among cars while reducing the wireless interface's contention.

This work has been published in [19].

8.24 Fog Services Provider – FSP – architecture for IoT with a unified semantic data model

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

The prominence of Internet of Things (IoT) devices is characterized by a wide diversity of network access technologies, including Wi-Fi, Cellular, Lo-Ra, ZigBee, or Bluetooth. Dealing with such heterogeneity is still very challenging in devices, communication technologies, protocols, data formats, and semantics. Current cloud computing solutions can sustain a considerable amount of diverse data generated by geographically spread IoT devices. However, this task is quite challenging for time-sensitive services. Moreover, IoT heterogeneous devices are always managed by different application systems, and there are no unified storage and management solutions for information on IoT devices. In this work, we propose a microservice-based architecture named Fog services Provider (FSP) that uses the FoG computing paradigm. The objective is to provide flexible management of heterogeneous devices. A novel aspect of this service architecture is to build a general data model to describe and store data of IoT heterogeneous devices based on Semantic Web technologies. We also propose a data converting algorithm from relational databases to a unified format and demonstrates procedures with effective management to register and access those devices into FSP architecture. Furthermore, data generated from diverse sources use different semantics and models. It makes semantic interoperability an outstanding issue in providing seamless communication and services over various IoT platforms. Semantic models are a useful approach for exchanging semantically annotated information between heterogeneous applications. Seamless communication between different types of applications is usually achieved using middleware, ontology, semantic web technologies, and there are no unified storage and management methods for information on IoT devices. In this case, we extend the FSP architecture with a semantic data model for a generic description of elements to support IoT.

This work has been published in [25, 26].

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

MLNS

Title: Machine Learning, Network, System and Security

Duration: 2021 - 2023

Coordinator: Alain Tchana (ENS-Lyon)

Partners:

- WIDE and TRiBE Inria Project-Teams
- Université of Yaoundé I,

Inria contact: Aline C. Viana

Summary: The MLNS associate team supports and develops a collaboration between Université of Yaoundé I and Inria Saclay (team TRiBE and WIDE) in the domain of cybersecurity in cellular networks. The aim of this collaboration is to adequately design and investigate efficient approaches to fight against simbox frauds and malware proliferation. Addressing related challenges require multidisciplinary knowledge such as Machine Learning, Network, System, and Security (MLNS2). Having these four areas of expertise in the same research team is rare, and this is one of the strengths of this collaboration. Our scientific goal is to bridge the gap between each of these four areas of expertise while leveraging our ongoing joint works. In particular: (1) in Addressing simbox frauds and (2) in Addressing malware proliferation via on-device antiviruses.

PSAR

Title: Physical Security Applied to (R)IOT

Duration: 2020 - 2022

Coordinator: Emmanuel Baccelli

Partners:

- Freie Universität Berlin (Germany)

Inria contact: Emmanuel Baccelli

Summary: The PSAR associate team supports and develops a collaboration between Freie Universität Berlin and Inria Saclay (team TRiBE) in the domain of cybersecurity for the Internet of Things. The work aims to complement the security mechanisms tackled in the Inria Challenge RIOT-fp. RIOT-fp focuses on enhancing the security of IoT devices running RIOT via (1) lower-memory, high-speed, high-security IoT crypto primitives, (2) guarantees for software execution on low-end IoT devices, and (3) enabling secure IoT software updates, over low-power IP protocols. PSAR focuses on complementary schemes exploiting physical characteristics to secure IoT devices running RIOT, namely (i) Physically Unclonable Functions for IoT device authentication, (ii) exploiting the physical network layer for secure communication bootstrapping, and (iii) holistic approaches and mechanisms enabling, remote, periodic "health checks" for IoT deployments that are up and running.

10.1.2 Inria international partners

Declared Inria international partners

- Freie Universität Berlin (Germany) (PSAR Associated team of Inria)
- Université of Yaoundé I (MLNS Associated team of Inria)
- Federal University of Minas Gerais (jointly PhD aggrement)
- Federal University of Bahia (jointly PhD aggrement)
- University of Chile (jointly PhD aggrement)
- LNCC (Inria international joint lab)

Informal international partners

- All the information partners are mentioned in our joint publications and project

10.2 International research visitors

10.2.1 Visits of international scientists

- Kleber Vieira Cardoso, Federal University of Goias, Brasil
- Sand Correa, Federal University of Goias, Brasil

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.

10.4 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.

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.

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: 2020–2023
- Coordinator: Aline Carneiro Viana
- Other partners: COMETE/Inria, Universite de la Rochelle, Sorbonne Universite.
- 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

At Inria:

- Inria Transfer and Development Action (ADT project): entitle "How mobile can a Mobile Edge Computing be?"

"How mobile can a Mobile Edge Computing be?"

Participants Nadjib Achir, Aline Carneiro Viana, Pedro Cruz.

- Funding instrument/scientific committee: Inria Transfer and Development Action funding
- Duration: 2020–2023
- Coordinator: Nadjib Achir
- Abstract: 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

11.1 Promoting scientific activities

11.1.1 Scientific events: organisation

General chair, scientific chair

- Emmanuel Baccelli, co-chair of RIOT Summit 2020, and PEMWN 2020.
- 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.
- Aline C. Viana: General and TPC co-chair of MobiArch 2020 jointly with ACM MobiCom 2020.

Member of the organizing committees

- Nadjib Achir: (1) Workshop co-chair of EuCNC & 6G Summit'21 (2) Publicity co-chair of ACM SenSys 2021.
- Aline C. Viana: (1) Publicity co-chair of ESWN 2020; (2) Workshop co-chair of IEEE MASS 2021. Sponsorship co-chair of ACM SenSys 2021.
- Emmanuel Baccelli: IEEE European Symposium on Security and Privacy: Tutorial on IoT Security with Microcontrollers & RIOT.

11.1.2 Scientific events: selection

Chair of conference program committees

- Cédric Adjih, TPC co-chair of PEMWN2020.
- Aline C. Viana: General and TPC co-chair of MobiArch 2020 jointly with ACM MobiCom 2020.

Member of the conference program committees

- Aline C. Viana: (1) ACM MSWIM 2020; (2) Algotel 2020.
- Nadjib Achir, MSWIM'20, EuCNC'20, PIMRC'20, 5G-WF'20, Globecom2020.

Reviewer

- Cedric Adjih, Globecom2020, GIIS'20, CSNet'20, PEMWN2020, COMNETSAT 2020, ICC 2021.

11.1.3 Journal

Member of the editorial boards

- (since Jul. 2019) Editorial Board member of *Ad Hoc Networks Elsevier Journal*.
- (since Feb. 2018) Editorial Board member of *Urban Computing Spring book series* (http://www.springer.com/series/15552).
- (since May 2014) Area editor of *ACM SIGCOMM Computer Communication Review* – ACM CCR.

Reviewer - reviewing activities

- Nadjib Achir, acted as reviewer for Journal of Sensor and Actuator Networks (JSAN) - MDPI, IEEE Systems Journal
- Emmanuel Baccelli, ACM Computing Surveys, IEEE IoT Journal, Elsevier Future Generation Computer Systems Journal, IETF Routing Directory

11.1.4 Invited talks

- In Feb. 2020, Emmanuel Baccelli gave an invited talk at the COP Inria Ceremony on *"RIOT-fp: Projet de Recherche à Risque sur l'Internet des Objets"*.

- In March 2020, Cédric Adjih gave an invited talk on "Machine Learning for IoT (TinyML)" at the DigiCosme Seminar of WG "Future Access Network" (slides).

- In Nov. 2020, Emmanuel Baccelli gave an invited talk at the Berlin Science Week, on *"CyberSafety, CyberSecurity, CyberPrivacy? The Long-term Challenges of Open & Secure IoT Ecosystems"*.

- In Jan. 2021, Aline C. Viana was a Keynote at LastMile 2021 workshop ("Last-mile" Challenges and Standardization Opportunities in Smart Infrastructure) jointly with COMSNETS 2021 on "Motion intelligence toward efficient Internet edges".

- In Nov. 2020, Aline C. Viana participated to the invited talk at the STIC AmSud COVID workshop ("The STIC science applied to health and the example of Covid-19") on the SafeCityMap Inria-Covid workshop.

- In Nov. 2020, Philippe Jacquet was a Keynote at Machine Learning in Networking event.

11.1.5 Leadership within the scientific community

- Emmanuel Baccelli initiated and leads the **Challenge Inria RIOT-fp**, which federates and articulates research activities of 5 Inria project-teams (TRiBE, EVA, TEA, GRACE and PROSECCO) as well as Freie Universität Berlin on research topics around cybersecurity, formal verification for low-power IoT software and high-performance, low-footprint cryptography, leveraging RIOT as experimental platform.

- Emmanuel Baccelli was tasked by the scientific directors of Inria to coordinate the production of a new Inria white book, aiming to capture the wide landscape of challenges relating to IoT: to synthetize the key future research aspects, as well as the main societal problems which pertain to IoT. As such Emmanuel Baccelli initiated and coordinates the input of 30+ Inria project-teams on a document which is expected to be published in 2021.

11.1.6 Research administration

- Aline C. Viana is the leader of the TRiBE Project-Team of Inria since its creation (Jul.2019); She was the leader of the previous INFINE project-team for one year 2018-2019.

- Aline C. Viana is the coordinator of ANR MITIk (2020-) and SafeCityMap, and Inria-Covid mission project (2020-).

- Aline C. Viana is 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.

- Philippe Jacquet is the coordinator of Ariadne COVID, Inria-Covid mission project (2020-).

- Emmanuel Baccelli is the co-founder and coordinator of the RIOT community, which federates hundreds of contributors worldwide, and which has generated hundreds of academic publications since 2013. Within Inria, Emmanuel Baccelli leads the team of RIOT contributors including TRiBE-affiliated members Koen Zandberg, Alexandre Abadie, Francois-Xavier Molina and Kaspar Schleiser.

11.2 Teaching - Supervision - Juries

11.2.1 Teaching

- Master : Emmanuel Baccelli, “IoT & Security”, summer semester seminar (April 2020 - June 2020), Freie Universitaet Berlin.
- Master : Emmanuel Baccelli, “IoT & Security”, winter semester seminar (Oct 2020 - Jan 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. 2020.
- Engineering School: Cédric Adjih, “Internet of Things”, 12h lab sessions in 2020, ENSEA.

11.2.2 Supervision

- PhD in progress: Abhishek Kumar Mishra, “Trajectory reconstruction and contact tracing from non-intrusive passive measurements”, since Aug. 2020 . Advisors: Aline C. Viana, Nadjib Achir.
- PhD in progress: Licia Amichi, “Identifying and profiling novelty-seeking behavior in human mobilityModelling exploration factor of human beings”, since Oct. 2018. Advisor: Aline C. Viana.
- PhD in progress: Douglas Teixeira, “Deciphering Predictability Limits in Human Mobility”, since April 2018. Advisor: Aline C. Viana and Jussara Almeida.
- PhD in progress: Rafael Costa, “Human-enhanced forwarding strategies for Device-to-Device (D2D) communication”, since May 2017. Advisor: Aline C. Viana and Leobino Sampaio.
- PhD in progress: Diego Madriaga, “Short-term Time Series Analysis and Prediction for Anticipatory Networking”, since Jan 2019. Advisor: Aline C. Viana and Javier Bustos.
- PhD in progress: Anne Josiane Kouam Djuigne, “Detection of bypass frauds in cellular network datasets”, since Nov 2019. Advisor: Aline C. Viana and Alain Tchana.
- PhD in progress: Hirah Malik, “Efficient COding of Meta-information in Information-CEntric NEtworks”, since Oct. 2017. Advisors: C. Adjih, Michel Kieffer, and Claudio Weidmann.
- PhD in progress: Iman Hmedoush, “Connection protocols for the 5G IoT”, since Oct. 2018. Advisors: C. Adjih and Paul Mühlethaler.
- PhD in progress: Koen Zandberg, “Cybersecure Multi-Tenant Microcontroller-based IoT”, since Feb. 2020. Advisor: Emmanuel Baccelli.
- PhD in progress: Larissa Groth, “Low-power Software Bill of Materials Attestation”, since June 2020. Advisors: Emmanuel Baccelli and Jochen Schiller.

11.2.3 Juries

- **Reviewer for PhD thesis committee:**
  - Emmanuel Baccelli was reviewer for the following PhD: Mathieu Thiery (Université Grenoble-Alpes, Nov. 2020).
  - Aline C. Viana was a reviewer for the committees of the following PhD: V. S. H. Huynh (Univ. of Nottingham, UK, Jul. 2020).
- **Examiner for PhD thesis committee:**
  - Nadjib Achir was examiner for the committees of the following PhDs: Sarra Mehamel (CNAM, Nov. 2020); Giacomo Quadrio (University of Padova, Jan. 2021).

  - Cédric Adjih was examiner for the committees of the following PhD: Asma LAHBIB (IPP TSP, Nov. 2020).
  - Aline C. Viana was an examiner for the committees of the following PhDs: C. Bertier (Thales/Sorbonne Univ., Jan. 2020); J. Levy Abitbol (ENS Lyon/DANTE, Jan. 2020); Y. Du (UPMC/Inria, Jun. 2020); A. Blaise (also jury President, CNAM, Dec. 2020); R. Ladjel (Univ. ParisSaclay/Inria, Dec. 2020); L. Santos (Federal University of Minas Gerais, Feb. 2021).

- **Examiner for PhD mid-term committee:**

  - Nadjib Achir was an examiner for the committees in the following PhDs' mid-term: Fouzi BOUKHALFA (Inria/VEDECOM, Nov. 2020).

11.3 Popularization

11.3.1 Internal or external Inria responsibilities

For Aline C. Viana:

- At Inria:

  - 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.
  - Aline C. Viana is the coordinator of the ANR MITIK project (2020-) and Inria SafeCityMap of Inria-COVID mission (2020-).
  - 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.
  - Aline C. Viana is co-Coordinator of the mentoring program for researchers at Inria Saclay (https://project.inria.fr/mentoratscl/). 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.

- At the regional eco-system:

  - 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:

  - (2020) Member of the Selection Committee for a Professor and an Assistant Professor positions at the Polytechnique School/IPP.
  - (2021) Member of the Selection Committee for an Assistant Professor position at the IUT/Université de La Rochelle".

11.3.2 Education

- Emmanuel Baccelli co-authored a massive open online course (MOOC) on Internet of Things on Microcontrollers (a hands-on course). From March to May 2020, there were 7k participants, from 100+ countries (33 percent from industry) and 500+ were certificates delivered. Online website.

11.3.3 Interventions

- Panelist at the 2nd edition of MUSAS event of SBRC 2020 (Brazilian biggest conference in networking and telecommunication). The goal of this events is to help female students and researchers pursue research carriers. *Some panel topics:* "How to overcome the job search challenges?"; "How to have a successful transition form graduate school to a full job position?".
- *Speaker at "Unithé ou Café" of INRIA Saclay (January 2020):* an open 45-minute coffee meeting organized by the Communication Service of INRIA Saclay with all administrative employees and researchers. *Title:* "SafeCityMap project, Mission Covid Inria".

12 Scientific production

12.1 Major publications

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

[2] S. Faiz, N. Achir and K. Boussetta. 'On the benefits of increased vehicles perception to cooperative communications'. In: *ACM MobiArch 2020 The 15th Workshop on Mobility in the Evolving Internet Architecture*. Londres / Virtual, United Kingdom: ACM, Sept. 2020, pp. 16–21. DOI: 10.1145/3411043.3412504. URL: https://hal.archives-ouvertes.fr/hal-03045508.

[3] H. Fawaz, K. Khawam, S. Lahoud, C. Adjih and S. Martin. 'Joint spreading factor and channel assignment in multi-operator lorawan deployments'. In: *Sensors* 21.1 (2021), pp. 1–19. DOI: 10.3390/s21010162. URL: https://hal.archives-ouvertes.fr/hal-03127504.

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

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

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

[7] 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* (2021). DOI: 10.1016/j.comnet.2021.107816. URL: https://hal.archives-ouvertes.fr/hal-02887550.

[8] G. Restuccia, H. Tschofenig and E. Baccelli. 'Low-Power IoT Communication Security: On the Performance of DTLS and TLS 1.3'. In: *PEMWN 2020 - 9th IFIP/IEEE International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks*. Berlin / Virtual, Germany, Dec. 2020. URL: https://hal.inria.fr/hal-03035402.

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

12.2 Publications of the year

International journals

[10] R. L. Costa, A. C. Viana, A. Ziviani and L. N. Sampaio. 'Tactful Networking: Humans in the Communication Loop'. In: *IEEE Transactions on Emerging Topics in Computational Intelligence* (7th Dec. 2020). DOI: 10.1109/TETCI.2020.3039520. URL: https://hal.inria.fr/hal-03139281.

[11] 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.

[12] P. Jacquet and B. Mans. 'Blockchain moderated by empty blocks to reduce the energetic impact of crypto-moneys'. In: *International Journal of Computers, Communications and Control* (2020). URL: https://hal.archives-ouvertes.fr/hal-03126614.

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

[14] 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* (2021). DOI: 10.1016/j.comnet.2021.107816. URL: https://hal.archives-ouvertes.fr/hal-02887550.

International peer-reviewed conferences

[15] L. Amichi, A. Carneiro Viana, M. Crovella and A. A. F. Loureiro. 'Understanding individuals' proclivity for novelty seeking'. In: ACM SIGSPATIAL 2020 - 28th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems. Seattle, Washington, United States, 3rd Nov. 2020. URL: https://hal.inria.fr/hal-02944150.

[16] F. Boukhalfa, C. Adjih, P. Muhlethaler, M. Hadded and O. Shagdar. 'Physical and MAC Layer Design for Active Signaling Schemes in Vehicular Networks'. In: STWiMob 2020 - 16th International Workshop on Selected Topics in Wireless and Mobile computing. Thessaloniki / Virtual, Greece, 12th Oct. 2020. URL: https://hal.archives-ouvertes.fr/hal-02983311.

[17] T. Claeys, F.-X. Molina, M. Vucinic, T. Watteyne and E. Baccelli. 'RIOT and OpenWSN 6TiSCH: Happy Together'. In: PEMWN 2020 - 9th IFIP/IEEE International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks. Berlin / Virtual, Germany, 1st Dec. 2020. URL: https://hal.inria.fr/hal-03064601.

[18] 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: https://infocom2021.ieee-infocom.org/, 10th May 2021. URL: https://hal.inria.fr/hal-03140370.

[19] S. Faiz, N. Achir and K. Boussetta. 'On the benefits of increased vehicles perception to cooperative communications'. In: ACM MobiArch 2020 - 15th Workshop on Mobility in the Evolving Internet Architecture. Londres / Virtual, United Kingdom: http://cosafe.org.uk/mobiarch2020.html, 21st Sept. 2020, pp. 16–21. DOI: 10.1145/3411043.3412504. URL: https://hal.archives-ouvertes.fr/hal-03045508.

[20] 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.

[21] I. Hmedoush, C. Adjih, P. Muhlethaler and V. Kumar. 'On the Performance of Irregular Repetition Slotted Aloha with Multiple Packet Reception'. In: IWCMC 2020 - 16th International Wireless Communications and Mobile Computing Conference. Limassol / Virtual, Cyprus: https://iwcmc.org/2020/, 15th June 2020, pp. 557–564. DOI: 10.1109/IWCMC48107.2020.9148173. URL: https://hal.inria.fr/hal-03136710.

[22] I. Hmedoush, C. Adjih, P. Muhlethaler and L. Salaun. 'Multi-Power Irregular Repetition Slotted ALOHA in Heterogeneous IoT networks'. In: PEMWN 2020 - 9th IFIP/IEEE International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks. PEMWN 2020 - 9th IFIP/IEEE International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks, Berlin / Virtual, Germany, 1st Dec. 2020. URL: https://hal.archives-ouvertes.fr/hal-03043850.

[23] P. Jacquet, K. Turowski and W. Szpankowski. 'Power-Law Degree Distribution in the Connected Component of a Duplication Graph'. In: *31st International Conference on Probabilistic, Combinatorial and Asymptotic Methods for the Analysis of Algorithms (AofA2020)*. AofA2020 - 31st International Conference on Probabilistic, Combinatorial and Asymptotic Methods for the Analysis of Algorithms. Klagenfurt, Austria, 15th June 2020. URL: https://hal.archives-ouvertes.fr/hal-03123680.

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

[25] H. Le, N. Achir and K. Boussetta. 'Fog Services Provider Architecture for IoT'. In: *11th International Conference on Network of the Future (NoF)*. NoF 2020 - 11th International Conference on Network of the Future. Bordeaux, France, 14th Oct. 2020, pp. 8–15. DOI: 10.1109/NoF50125.2020.9249177. URL: https://hal.archives-ouvertes.fr/hal-03045499.

[26] H. Le, K. Boussetta and N. Achir. 'A unified and semantic data model for fog computing'. In: GIIS 2020 - Global Information Infrastructure and Networking Symposium. Tunis / Virtual, Tunisia, 28th Oct. 2020, pp. 1–6. DOI: 10.1109/GIIS50753.2020.9248482. URL: https://hal.archives-ouvertes.fr/hal-03045495.

[27] R. Lima Costa, A. Carneiro Viana, A. Ziviani and L. N. Sampaio. 'Towards Human-Aware D2D Communication'. In: UrbCom 2020 - 2nd International Workshop on Urban Computing. Los Angeles, United States, 15th June 2020. URL: https://hal.inria.fr/hal-02931013.

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

[29] H. Malik, C. Adjih, M. Kieffer and C. Weidmann. 'Analysis of the properties of NetcodICN protocols'. In: CORES 2020 - 5ème Rencontres Francophones sur la Conception de Protocoles, l'Évaluation de Performance et l'Expérimentation des Réseaux de Communication. Lyon, France, 28th Sept. 2020. URL: https://hal.archives-ouvertes.fr/hal-02866093.

[30] H. Malik, C. Adjih, M. Kieffer and C. Weidmann. 'On the Problem of Finding "Sets Ensuring Linearly Independent Transversals" (SELIT), and its Application to Network Coding'. In: PEMWN 2020 - 9th IFIP/IEEE International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks. Berlin / Virtual, Germany, 1st Dec. 2020. URL: https://hal.inria.fr/hal-03066183.

[31] G. Restuccia, H. Tschofenig and E. Baccelli. 'Low-Power IoT Communication Security: On the Performance of DTLS and TLS 1.3'. In: PEMWN 2020 - 9th IFIP/IEEE International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks. Berlin / Virtual, Germany, 1st Dec. 2020. URL: https://hal.inria.fr/hal-03035402.

[32] K. Zandberg and E. Baccelli. 'Minimal Virtual Machines on IoT Microcontrollers: The Case of Berkeley Packet Filters with rBPF'. In: PEMWN 2020 - 9th IFIP/IEEE International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks. Berlin / Virtual, Germany: https://sites.google.com/view/pemwn2020, 1st Dec. 2020. URL: https://hal.inria.fr/hal-03019639.

Conferences without proceedings

[33] L. Amichi, A. C. Viana, M. Crovella and A. A. F. Loureiro. 'Explorateur ou Routinier: Quel est votre profile de mobilité?' In: ALGOTEL 2020 – 22èmes Rencontres Francophones sur les Aspects Algorithmiques des Télécommunications. Lyon, France, 29th Sept. 2020. URL: https://hal.archives-ouvertes.fr/hal-02868049.

[34] I. Hmedoush, C. Adjih and P. Muhlethaler. 'A Regret Minimization Approach to Frameless Irregular Repetition Slotted Aloha: IRSA-RM'. In: MLN 2020 - International Conference on Machine Learning for Networking. MLN 2020 - International Conference on Machine Learning for Networking. Paris / Virtual, France, 24th Nov. 2020. URL: https://hal.archives-ouvertes.fr/hal-03043877.

[35] P. Jacquet and W. Szpankowski. 'Analysis of Lempel-Ziv'78 for Markov Sources'. In: AofA2020 - 31st International Conference on Probabilistic, Combinatorial and Asymptotic Methods for the Analysis of Algorithms. Klagenfurt, Austria, 15th June 2020. DOI: 10.4230/LIPIcs.AofA.2020.15. URL: https://hal.archives-ouvertes.fr/hal-03139593.

[36] D. Popescu, P. Jacquet and B. Mans. 'Connecting flying backhauls of UAVs to enhance vehicular networks with fixed 5G NR infrastructure'. In: *IEEE INFOCOM 2020-IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*. IEEE INFOCOM 2020-IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS). IEEE, 2020. Toronto, Canada, 2020. URL: https://hal.archives-ouvertes.fr/hal-03034853.

Reports & preprints

[37] 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.

[38] L. Brotcorne, A. Canteaut, A. C. Viana, C. Grandmont, B. Guedj, S. Huot, V. Issarny, G. Pallez, V. Perrier, V. Quema, J.-B. Pomet, X. Rival, S. Salvati and E. Thomé. *Indicateurs de suivi de l'activité scientifique de l'Inria*. Inria, 1st Dec. 2020. URL: https://hal.inria.fr/hal-03033764.

[39] 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.

[40] 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.

[41] P. Jacquet. *The Ariadne String against Covid-19 pandemic propagation part 2: oudoor path selection after lock-downs*. 18th May 2020. URL: https://hal.archives-ouvertes.fr/hal-02611833.

[42] P. Jacquet, S. Gil I. and W. Szpankowski. *Precise Minimax Regret for Logistic Regression with Categorical Feature Values*. 2nd Dec. 2020. URL: https://hal.archives-ouvertes.fr/hal-03034844.

[43] P. Jacquet and L. Tupikina. *The Ariadne String against COVID -19 pandemic propagation: outdoor path selection with limited virus exposure*. 20th Oct. 2020. URL: https://hal.inria.fr/hal-02972887.

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

[45] A. J. Kouam, A. Carneiro Viana and A. Tchana. *SIMBox bypass frauds in cellular networks: a survey*. INRIA, 2021. URL: https://hal.inria.fr/hal-03105845.

[46] A. K. Mishra, A. C. Viana and N. Achir. *SimBle: Generating privacy preserving real-world BLE traces with ground truth*. 29th Jan. 2021. URL: https://hal.inria.fr/hal-03125920.

[47] D. Popescu, P. Jacquet, B. Mans and B. Błaszczyszyn. *Characterizing the Energy Trade-Offs of End-to-End Vehicular Communications using an Hyperfractal Urban Modelling*. 1st Dec. 2020. URL: https://hal.archives-ouvertes.fr/hal-03034848.

[48] D. Teixeira, J. M. Almeida and A. Carneiro Viana. *Understanding routine impact on the predictability estimation of human mobility*. 2nd Feb. 2021. URL: https://hal.inria.fr/hal-03128624.

[49] D. D. C. Teixeira, A. Carneiro Viana, J. M. Almeida and M. S. Alvim. *Revealing challenges in human mobility predictability*. 2nd Feb. 2021. DOI: 10.1145/1122445.1122456. URL: https://hal.inria.fr/hal-03128639.

Other scientific publications

[50] B. Moran, H. Tschofenig, H. Birkholz and K. Zandberg. *A Concise Binary Object Representation (CBOR)-based Serialization Format for the Software Updates for Internet of Things (SUIT) Manifest*. 13th July 2020. URL: https://hal.inria.fr/hal-03137962.

[51] M. Saito, M. Matsumoto, V. Roca and E. Baccelli. *TinyMT32 Pseudorandom Number Generator (PRNG) (RFC 8682)*. 15th Jan. 2020. URL: https://hal.inria.fr/hal-02449210.

12.3 Cited publications

[52] L. Santos De Oliveira, P. O. Vaz De Melo and A. Carneiro Viana. 'Measuring Power Relations Among Locations From Mobility Data'. In: *ACM MobiWac 2019 - 17th ACM International Symposium on Mobility Management and Wireless Access*. Miami, United States, Nov. 2019. URL: https://hal.inria.fr/hal-02302490.