



Activity Report 2016

Project-Team FUN

self-organizing Future Ubiquitous Network

RESEARCH CENTER
Lille - Nord Europe

THEME
Networks and Telecommunications

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Project-Team FUN

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- 5.6. - Robotic systems
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- 6.4. - Internet of things
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- 8. - Smart Cities and Territories

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2. Overall Objectives

2.1. Overall Objectives

Context.

The Internet of Things [62] is a large concept with multiple definitions. However, the main concepts are the same in every vision and could be summed up as follows: *Imagine a world where every object has the capacity to communicate with its environment. Everything can be both analogue and digitally approached - reformulates our relationship with objects - things - as well as the objects themselves. Any object relates not only to you, but also to other objects, relations or values in a database. In this world, you are no longer alone, anywhere.* (Internet of Things council).

Future Ubiquitous Networks (FUN) are part of the Internet of Things. They are composed of tens to thousands heterogeneous hardware-constrained devices that interact with our environment and the physical world. These devices have limited resources in terms of storage and computing capacities and energy. They communicate through unreliable and unpredictable short-range wireless links and run on batteries that are not envisaged to be changed in current systems since generally deployed in hostile environments. Providing FUNs with energy saving protocols is thus a key issue. Due to these specific features, any centralized control is not conceivable, the new generation of FUNs must be autonomous, be self-organized and dynamically adapt to their environment. The devices that compose CPNs can be sensors, small robots, RFID readers or tags.

Objects or things can now communicate with their environment through the use for instance of an RFID (Radio Frequency IDentification) tag that provides them a unique identifier (ID) and a way to communicate through radio waves.

In the case of a simple passive **RFID tag**, the thing only embeds a tag equipped with an antenna and some memory. To communicate, it needs to be powered by the electromagnetic field of an RFID reader. This reader may then broadcast the information read on tag over a network.

When this tag is equipped with a battery, it is now able to communicate with nearby things similar to itself that may relay its message. Tags can also be equipped with additional capacity and sensors (for light, temperature, etc...). The Internet of Things can thus now refer to a **wireless sensor** network in which each sensor sends the data it collects over its environment and then sends it to a sink, *i.e.* a special sensor node able to analyze those data. In every case, RFID tags or sensor nodes can **be moved unexpectedly** like hold by moving things or animals. We speak then about '**undergone mobility**'.

So far, things can thus communicate information about their environment. But when the capacity of sensors is extended even further, they can also act on their environment (for instance, the detection of an event (fire) may trigger an action like switching the light or fire hoses on). Sensor nodes become **actuators**. When this extended capacity is the faculty to move, actuators are also referred as actors or robots. In this latter case, the mobility is computed on purpose, we then speak about '**controlled mobility**'. Actuators are not moved but move by themselves.

The FUN research group aims to focus on self-organizing techniques for these heterogeneous Future Ubiquitous Networks (FUNs). FUNs need various self-organization techniques to work properly. Self-organization encompasses neighbor discovery (which what other devices a sensor/actuator can communicate directly?), communication, self-deployment, self-localization, activity scheduling (when to wake up, when to send data to save energy without being detrimental to the well behavior of the network, etc)...

Solutions provided by FUN should facilitate the use of FUNs and rub away heterogeneity and difficulties. These techniques should be **scalable, energy-aware, standard-compliant**, should manage undergone **mobility** and take advantage of controlled mobility when available [72].

Solutions provided by FUN will consider vagaries of the realistic wireless environment by integrating cross-layer techniques in their design.

Motivation.

To date, many self-organizing techniques for wireless sensor networks and mobile ad hoc networks arise in the literature and also from the POPS research group. Some of them are very efficient for routing [64], [61], discovering neighborhood [69], [68], scheduling activity and coverage [66], localizing [73], [60], etc. Nevertheless, to the best of our knowledge, most of them **have not been validated by experimentation**, only by simulation and thus cannot consider the real impact of the wireless links and real **node mobility** in different environments. In addition, some of them rely on assumptions that are known not to be true in realistic networks such as the fact that the transmission range of a node is a perfect disk. Other may perform well only when nodes are static. None of them considers to **take advantage of controlled mobility** to enhance performances. Similarly, many propositions arise regarding self-organization in RFID networks, mainly at the middleware level [76], [65] and at the MAC layer level [58]. Although these latter propositions are generally experimented, they are validated only in static environments with very few tags and readers. To fit realistic features, such algorithms should also be evaluated with regards to scalability and mobility.

RFID and sensor/actor technologies **have not been merged**. Though, RFID readers may now be mobile and communicate in a wireless peer-to-peer manner either with other RFID readers or wireless sensor nodes and all belong to the same network. This implies a study of the standards to allow inter-dependencies in a transparent manner. Although such works have been initiated inside EPC Global working groups, research actions remain scarce.

FUN research group aims at **filling this scientific gap** by proposing self-stabilizing solutions, considering vagaries of wireless links, node mobility and heterogeneity of nodes in compliance with current standards. Validation by experimentation is mandatory to prove the effectiveness of proposed techniques in realistic environments.

FUN will investigate new protocols and communication paradigms that allow the **transparent merging** of technologies. Objects and events might interconnect while **respecting on-going standards** and building an autonomic and smart network while being compliant with hardware resources and environment. FUN expects to rub away the difficulty of use and programmability of such networks by unifying the different technologies. In addition, FUN does not only expect to validate the proposed solutions through experimentation but also to learn from these experiments and from the observation of the impact of the wireless environment to take these features into consideration in the design of future solutions.

3. Research Program

3.1. Introduction

We will focus on wireless ubiquitous networks that rely on constrained devices, i.e. with limited resources in terms of storage and computing capacities. They can be sensors, small robots, RFID readers or tags. A wireless sensor retrieves a physical measure such as light. A wireless robot is a wireless sensor that in addition has the ability to move by itself in a controlled way. A drone is a robot with the ability to manoeuvre in 3D (in the air or in the water). RFID tags are passive items that embed a unique identifier for a place or an object allowing

accurate traceability. They can communicate only in the vicinity of an RFID reader. An RFID reader can be seen as a special kind of sensor in the network which data is the one read on tags. These devices may run on batteries that are not envisaged to be changed or recharged. These networks may be composed of ten to thousands of such heterogeneous devices for which energy is a key issue.

Today, most of these networks are homogeneous, i.e. composed of only one kind of devices. They have mainly been studied in application and technology silos. Because of this, they are approaching fundamental limitations especially in terms of topology deployment, management and communications, while exploiting the complementarity of heterogeneous devices and communication technologies would enlarge their capacities and the set of applications. Finally, these networks must work efficiently even in dynamic and realistic situations, i.e. they must consider by design the different dynamic parameters and automatically self-adapt to their variations.

Our overall goal is represented by Figure 1. We will investigate wireless ubiquitous IoT services for constrained devices by smartly combining **different frequency bands** and **different medium access and routing techniques** over **heterogeneous devices** in a **distributed** and **opportunistic** fashion. Our approach will always deal with **hardware constraints** and take care of **security** and **energy** issues to provide protocols that ride on **synergy** and **self-organization** between devices.

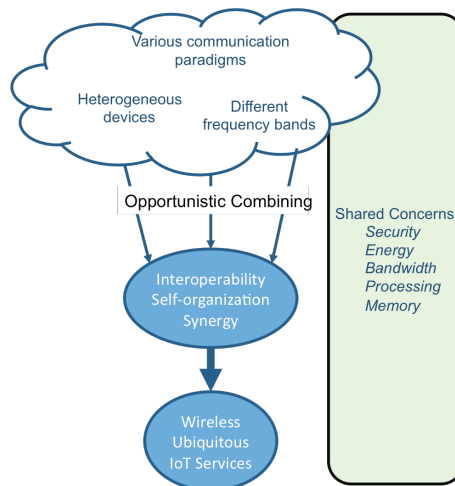


Figure 1. FUN's overall goal.

The goal of the FUN project team is to provide these next generation networks with a set of innovative and distributed self-organizing cooperative protocols to raise them to a new level of scalability, autonomy,

adaptability, manageability and performance. We aim to break these silos to exploit the full synergy between devices, making them cooperate in a single holistic network. We will consider them as networks of heterogeneous devices rather than a collection of heterogeneous networks.

To realize the full potential of these ubiquitous networks, there is a need to provide them with a set of tools that allow them to (i) (self-)deploy, (ii) self-organize, (iii) discover and locate each other, resources and services and (iv) communicate. These tools will be the basics for enabling cooperation, co-existence and witnessing a global efficient behavior. The deployment of these mechanisms is challenging since it should be achieved in spite of several limitations. The main difficulties are to provide such protocols in a **secured** and **energy-efficient** fashion in spite of :

- dynamic topology changes due to various factors such as the unreliability of the wireless medium, the wireless interferences between devices, node mobility and energy saving mechanisms;
- hardware constraints in terms of CPU and memory capacities that limit the operations and data each node can perform/collect;
- lacks of interoperability between applicative, hardware and technological silos that may prevent from data exchange between different devices.

3.1.1. Objectives and methodology

To reach our overall goal, we will pursue the two following objectives, similar to the ones we set for the previous evaluation period. These two objectives are orthogonal and can be carried on jointly :

1. Providing realistic complete self-organizing tools *e.g. vertical perspective.*
2. Going to heterogeneous energy-efficient performing wireless networks *e.g. horizontal perspective,*

We give more details on these two objectives below. To achieve our main objectives, we will mainly apply the methodology depicted in Figure 2 combining both theoretical analysis and experimental validation. Mathematical tools will allow us to properly dimension a problem, formally define its limitations and needs to provide suitable protocols in response. Then, they will allow us to qualify the outcome solutions before we validate and stress them in real scenarios with regards to applications requirements. For this, we will realize proofs-of-concept with real scenarios and real devices. Differences between results and expectations will be analyzed in return in order to well understand them and integrate them by design for a better protocol self-adaptation capability.

3.2. Vertical Perspective

As mentioned, future ubiquitous networks evolve in dynamic and unpredictable environments. Also, they can be used in a large scope of applications that have several expectations in terms of performance and different contextual limitations. In this heterogeneous context, IoT devices must support multiple applications and relay traffic with non-deterministic pattern.

To make our solutions practical and efficient in real conditions, we will adopt the dual approach both *top-down* and *bottom-up*. The *top-down* approach will ensure that we consider the application (such as throughput, delay, energy consumption, etc) and environmental limitations (such as deployment constraints, etc). The *bottom-up* approach will ensure that we take account of the physical and hardware characteristics such as memory, CPU, energy capacities but also physical interferences and obstacles. With this integrated perspective, we will be in capacity to design **cross-layer** integrated protocols well adapted [39]. We will design jointly routing and MAC layers by taking dynamics occurring at the physical layer into account with a constant concern for energy and security. We will investigate new adaptive frequency hopping techniques combined with routing protocols [41], [50], [24]. Also, we will work on new scheduling techniques for TSCH (a MAC layer of IEEE 802.15.4e) that are able work under the above-mentioned assumptions and bring the robustness of TSCH to IoT scenarios. We will investigate the performance boundaries of TSCH in particular in terms of energy-efficiency of time synchronization [63], and will propose alternative approaches such as capture effect-based time synchronization in TSCH or opportunistic routing. Another technology we will consider is IEEE 802.15.4g, which provides communication ranges in the order of tens of kilometers. We will propose

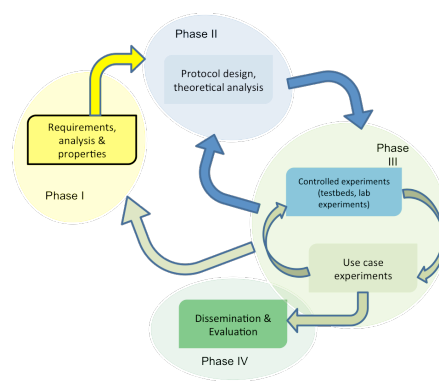


Figure 2. Methodology to be applied in FUN.

mechanisms to support scaling up to networks with a density of hundreds of nodes, at the MAC layer and above. We will also consider dual-technology networks where both long and short-range communication cooperate for increased robustness.

This vision will also allow us to integrate external factors by design in our protocols, in an opportunistic way. Yet, we will leverage on the occurrence of any of these phenomena rather than perceiving them as obstacles or limitations. As an example, we will rely on node undergone mobility to enhance routing performance as we have started to investigate in [74], [59]. On the same idea, when specific features are available like controlled mobility, we will exploit it to improve connectivity or coverage quality like in [46] [67].

3.3. Horizontal perspective

We aim at designing efficient tools for a plethora of wireless devices supporting highly heterogeneous technologies. We will thus investigate these networks from a horizontal perspective, e.g. by considering heterogeneity in low level communications layers.

Given the spectrum scarcity, they will probably need to coexist in the same frequency bands and sometimes for different purposes (RFID tag reading may use the same frequency bands as the wireless sensors). One important aspect to consider in this setting is how these different access technologies will interact with each other and what are the mechanisms needed to be put in place to guarantee that all services obtain the required share of resources when needed. This problem appears in different application domains, ranging from traffic offloading to unlicensed bands by cellular networks and the need to coexist with WiFi and radars, from a scenario in which multiple-purpose IoT clouds coexist in a city [75]. We will thus explore the dynamics of these interactions and devise ways to ensure smooth coexistence while considering the heterogeneity of the devices involved, the access mechanisms used as well as the requirements of the services provided.

To face the spectrum scarcity, we will also investigate new alternative communication paradigms such as phonon-based or light-based communications as we have initiated in [70], [71][16] and we will work on the coexistence of these technologies with traditional communication techniques, specifically by investigating efficient switching techniques from one communication technology to the other (they were most focused on the security aspects, to prevent jamming attacks). Resilience and reliability of the whole system will be the key factors to be taken into account [50], [24].

As a more prospective activity, we consider exploring software and communication security for IoT. This is challenging given that existing solutions do not address systems that are both constrained and networked [63]. Finally, in order to contribute to a better interoperability between all these technologies, we will continue to contribute to standardization bodies such as IETF and EPC Global.

4. Application Domains

4.1. Application Domains

The set of applications enabled through FUN and IoT is very large and can apply in every application area. We can thus not be exhaustive but among the most spread applications, we can name every area, event or animal monitoring, understanding and protection. To illustrate this, we may refer to the use cases addressed by our PREDNET project which goals is to equip rhinoceros with smart communicating devices to fight against poaching.

Other field of application is exploration of hostile and/or unknown environment by a fleet of self-organizing robots that cooperate with RFID and sensors to ensure a continue monitoring afterwards.

Also, IoT and FUN can play a key role in logistics and traceability by relying on the use of sensors or RFID technologies as implemented in our TRACAVERRRE project or our collaboration with the start up TRAXENS.

Finally, IoT and FUN leverage a lot of applications in Smart City concept , ranging from parking aid to a better energy consumption going through air quality monitoring, traffic fluidizing etc. (See our CityLab Inria and VITAL projects).

5. Highlights of the Year

5.1. Highlights of the Year

- The FIT facility has become an "Infrastructure de Recherche" (Infrastructure for Research) by the CD TGIR.

5.1.1. Awards

- Aziz Mbacke and Jad Nassar won the of the Hackaton at the SenZations summer school 2016, which opened them the doors of the UpRise Festival (<http://uprisefestival.co/>).
- Best paper award at the PIMRC 2016 conference .
- Viktor Toldov recipient of the award "Pepite 2016": (<http://www.enseignementsup-recherche.gouv.fr/cid108805/3e-edition-du-prix-pepites-tremplin-pour-l-entrepreneuriat-etudiant-53-projets-recompenses.html>)

BEST PAPER AWARD:

[47]

V. TOLDOV, L. CLAVIER, V. LOSCRÍ, N. MITTON. *A Thompson Sampling Approach to Channel Exploration-Exploitation Problem in Multihop Cognitive Radio Networks*, in "27th annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)", Valencia, Spain, September 2016, <https://hal.inria.fr/hal-01355002>

6. New Software and Platforms

6.1. FIT IoT-Lab

Participants: Nathalie Mitton [correspondant], Julien Vandaele.

FIT IoT-LAB is a very large scale open testbed that features over 2700 wireless sensor nodes and more than 200 robots spread across six different sites in France. Nodes are either fixed or mobile and can be allocated in various topologies throughout all sites. A variety of wireless sensors are available, with different processor architectures (MSP430, STM32 and Cortex-A8) and different wireless chips (802.15.4 PHY at 800 MHz or 2.4 GHz). In addition, "open nodes" can receive custom wireless sensors for inclusion in IoT-LAB testbed. This platform is completely open and can be used by any one wishing to run experiment on wireless sensors and robots.

The Lille site displays 3 subsets of the platforms:

- Euratechnologies : this site features 256 WSN430 sensor nodes operating in the 2.4GHz band. 64 nodes are mobile, embedded on mobile trains.
- Haute Borne : this site features 256 M3 sensor nodes operating in the 2.4GHz band and 64 mobile robots (32 turtlebots and 32 wifibots) completely remotely programmable.
- Opennodes : this site will feature (opening beginning 2015) 64 hardware open slots to allow any one to plug his own hardware and benefits from the platform debugging and monitoring tools.

7. New Results

7.1. Routing

Participants: Nathalie Mitton, Mouna Masmoudi.

Geographic routing is an attractive routing strategy in wireless sensor networks. It works well in dense networks, but it may suffer from the void problem. For this purpose, a recovery step is required to guarantee packet delivery. Face routing has widely been used as a recovery strategy since proved to guarantee delivery. However, it relies on a planar graph not always achievable in realistic wireless networks and may generate long paths. In [23], [12], we propose GRACO, a new geographic routing algorithm that combines a greedy forwarding and a recovery strategy based on swarm intelligence. During recovery, ant packets search for alternative paths and drop pheromone trails to guide next packets within the network. GRACO avoids holes and produces near optimal paths. Simulation results demonstrate that GRACO leads to a significant improvement of routing performance and scalability when compared to the literature algorithms.

GRACO has first been designed in the general case. We then studied its applicability to the Virtual Power Plants and their specific data packets with different priorities [23], [12]. Indeed, the Smart Grid (SG) incorporates communication networks to the conventional electricity system in order to intelligently integrate distributed energy resources (DERs) and allow for demand side management. The move to Smart grid in developing countries has to cope with great disparities of ICT infrastructures even within the same city. Besides, individual DERs are often too small to be allowed access to energy market, likewise power utilities are unable to effectively control and manage small DERs. We propose the use of affordable and scalable wireless communication technology to aggregate geographically sparse DERs into a single virtual power plant. The enrollment of prosumers in the VPP is conditional to financial performance of the plant. Thus, the VPPs are dynamic and are expected to scale up as more and more prosumers are attracted by their financial benefits. the communication network has to follow this progression and therefore to be scalable and rapidly deploy-able. We present a routing algorithm for data communication within the VPP to support centralized, decentralized or fully distributed control of the VPP's DERs.

Based on this study, we adapted GRACO so it can fit the specific cases of Smart Grid [23], [12] and more specifically to the Neighbor Area Networks (NAN) of Smart Grids, or distribution segment of the power system in the smart grid (SG). The deployment of ICT to support conventional grid will solve legacy problems that used to prevent implementation of smart services such as smart metering, demand side management or the integration of Distributed Energy Resources (DERs) within the smart grid. We demonstrate the effectiveness of GRACO in terms of scalability, peer-to-peer routing, end-to-end delay and delivery rate.

In another context, we made the observation that typical betweenness centrality metrics neglect the potential contribution of nodes that are near but not exactly on shortest paths. The idea of [35] is to give more value to these nodes. We propose a weighted betweenness centrality, a novel metric that assigns weights to nodes based on the stretch of the paths they intermediate against the shortest paths. We compare the proposed metric with the traditional and the distance-scaled betweenness metrics using four different network datasets. Results show that the weighted betweenness centrality pinpoints and promotes nodes that are underestimated by typical metrics, which can help to avoid network disconnections and better exploit multipath protocols.

7.2. Cloud and IoT

Participants: Valeria Loscri, Nathalie Mitton, Riccardo Petrolo.

Innovative and effective solutions to the fragmentation issues in the Internet of Things (IoT) landscape have been designed and proof of concept have been implemented to show the feasibility and effectiveness of the Cloud of Things (CoT) paradigm. In other words, we have focused on the convergence of Web semantic technologies and the Cloud computing concept as key enabler of an horizontal integration of various IoT applications and platforms [21]. The heterogeneity has to be considered not only in terms of applications and platforms, but another "type of heterogeneity" that deserves to be considered and analyzed is based on different devices and their interoperability.

A feasible solution to make different and heterogeneous devices to "interoperate" is based on the exploitation of a gateway. In particular, we have considered a Gateway-as-a-Service (Gaas) in [36], where we have shown that it is an efficient and lightweight device, which can be shared between several final users. Through the container virtualization technologies, we have been able to show how several platform requirements can be met, in a context where constrained devices have been considered. This study has demonstrated the Gateway-as-a-Service (GaaS) effectiveness and its exploitability in several IoT contexts, such as smart home, buildings, farms, agriculture environments, etc.

A different and complementary, to the previous solutions, perspective of IoT paradigm is represented by the management of the huge amount of data that have to be treated in the different IoT based applications. In [45], an infer algorithm has been proposed and more specifically an Bayesian Inference Approach (BIA) with the aim objective to avoid the transmission of high spatio-temporal correlated data.

7.3. Resource management in FUN

Participants: Cristina Cano Bastidas, Valeria Loscri, Simon Duquennoy.

A standard solution for reliable low-power mesh networks was defined in IEEE802.15.4e-2012, through the new MAC layer TSCH. TSCH (Time-Slotted Channel Hopping) provides a globally synchronized network that enables scheduling and channel hopping. Our review paper [28] details the TSCH technology as well as the 6LoWPAN and 6TiSCH protocols. It gathers authors from all major open-source IoT OSES: Contiki, OpenWSN, RIOT and TinyOS. The paper presents architectural considerations when it comes to implementing portable TSCH stacks, and presents preliminary evaluation results.

TSCH networks require global synchronization. The more precise the synchronization, the more energy-efficient the network. We address the challenge of reaching micro-second time synchronization over multiple hops in TSCH networks [31], at low power. The key idea is to use two crystal oscillators, one at low-frequency for low-power timekeeping, one at high-frequency for intra-slot precision. Along with adaptive drift compensation, this method is proven effective through an experimental assessment.

Beaconing is usually employed to allow network discovery and to maintain synchronisation in mesh networking protocols, such as those defined in the IEEE 802.15.4e and IEEE 802.11s standards. Thus, avoiding persistent or consecutive collisions of beacons is crucial in order to ensure correct network operation. Beacons are also used in receiver-initiated medium access protocols to advertise that nodes are awake. Consequently, effective beacon scheduling can enable duty-cycle operation and reduce energy consumption. We propose [56] a completely decentralised and low-complexity solution based on learning techniques to schedule beacon transmissions in mesh networks. We show the algorithm converges to beacon collision-free operation almost surely in finite time and evaluate converge times in different mesh network scenarios.

In [54] we focus on new methods, architectures, and applications for the management of Cyber Physical Objects (CPOs) in the context of the Internet of Things (IoT). The book covers a wide range of topics related to CPOs, such as resource management, hardware platforms, communication and control, and control and estimation over networks. It also discusses decentralized, distributed, and cooperative optimization as well as effective discovery, management, and querying of CPOs. Other chapters outline the applications of control, real-time aspects, and software for CPOs and introduce readers to agent-oriented CPOs, communication support for CPOs, real-world deployment of CPOs, and CPOs in Complex Systems. There is a focus on the importance of application of IoT technologies for Smart Cities.

Finally, we address software security and in particular the challenge of formally verifying the source code of IoT OSES. This is the topic of the yet-to-be-started H2020 VESSEDIA project. Our preliminary study [32] demonstrated the feasibility of applying Frama-C to a memory allocation module of the Contiki OS.

7.4. Smart Cities

Participants: Nathalie Mitton, Valeria Loscri, Riccardo Petrolo.

Smart City represents one of the most promising, prominent and challenging Internet of Things (IoT) applications, but recent ICT trends suggest more and more that cities could also benefit from Cloud computing. The convergence of IoT paradigm and Cloud computing technology, can play a fundamental role for developing of highly level and organized cities form an ICT point of view, but it is of paramount importance to deal a critical analysis to identify the issues and challenges deriving from this synergy.

A novel perspective that we have considered as key factor for the realization of Future Internet is the role of the interconnected objects as active entities in the context of the networked systems [52]. With this perspective in mind, we have proposed CACHACA [43], a ranking mechanism for Sensor Networks that facilitate the discovery of services provided by each network element. Discovery functionality has been also considered in the context of VITAL project, since effective and accurate mechanisms to discover Inter-Connected Objects (ICOs) and new services represents a sine qua non condition to have effective exploration of data-sources that are appropriate for a specific business context as defined by an end-user [42] [11].

On the other hand, a Smart City is a kind of ecosystem characterized with different IoT solutions that have to cooperate and coexist and is in continuous expansion. In order to face with the integration and interoperability challenges of this ecosystem, we have considered VITAL-OS architecture that can monitor, visualize, and control all the operations of a city [44].

7.5. RFID

Participants: Nathalie Mitton, Abdoul Aziz Mbacke.

One of the devices under consideration by the FUN team is RFID. One of the main issues to widely deploy RFID reader is reader-to-reader collision. Indeed, when the electromagnetic fields of the readers overlap, a collision occurs on the tag laying in the overlapping section and cannot be read. Numerous protocols have been proposed to attempt to reduce them, but, remaining reading errors still heavily impact the performances and fairness of dense RFID deployments. In [33], [18] we introduce a new Distributed Efficient & Fair Anticollision for RFID (DEFAR) protocol. It reduces both monochannel and multichannel collisions as well as interference by a factor of almost 90% in comparison with the best state of the art protocols. The fairness of the medium access among the readers is improved to a 99% level. Such improvements are achieved applying a TDMA-based "server-less" approach and assigning different priorities to readers depending on their behavior over precedent rounds. A distributed reservation phase is organized between readers with at least one winning reader afterwards. Then, multiple reading phases occur within a single frame in order to obtain fast coverage and high throughput. The use of different reader priorities based on reading behaviors of previous frames also contributes to improve both fairness and efficiency. Simulation results show the robustness of the proposed solution in terms of different metrics such collision avoidance, fairness and coverage and in comparison with a centralized literature solution.

In order to ensure collision-free reading, a scheduling scheme is needed to read tags in the shortest possible time. We study in [37] this scheduling problem in a stationary setting and the reader minimization problem in a mobile setting. We show that the optimal schedule construction problem is NP-complete and provide an approximation algorithm that we evaluate our techniques through simulation.

7.6. Interferences and failures management

Participants: Nathalie Mitton, Viktor Toldov, Valeria Loscri, Simon Duquennoy.

In the recent years, the Machine-to-Machine (M2M) paradigm together with the integration of wireless sensors networks with the generic infrastructure via *6LoWPAN* require the implementation of ad hoc communication protocols at the Medium Access Control layer, that do not depend on pre-existing infrastructure. Channel hopping concept has more and more gained consensus as a viable and effective solution for wireless MAC layer coordination with time-synchronized channel hopping (TSCH). In [24] we propose a decentralized multichannel MAC coordination framework (DT-SCS) leveraging the concept of *pulse-coupled oscillators* at the MAC layer. In DT-SCS, nodes randomly join a channel and are automatically spread across the available channels. The nodes then achieve PCO-based coordination via the periodic transmission of beacon packets

at the MAC layer. As such, for channels with an equal number of nodes, DT-SCS converges to synchronized beacon packet transmission at the MAC layer in a completely uncoordinated manner. In order to combat the well-known phenomenon of Cross-Technology Interference (CTI) a cross-layer mechanism, CrossZig, has been implemented in [39], based on the exploitation of information at the physical layer in order to detect the presence of CTI in a corrupted packet.

A different perspective of the interference management has been considered in [47] and [41], where a novel solution to allow to secondary users the access of allocated spectrum has been proposed. The study has been based on the major consideration that a big bottleneck in cognitive radio systems is based on finding the best available channel as fast as possible.

A totally different approach to face the enormous quantity of data generated by IoT devices, is to try to reduce the sending of useless data, based on the adoption of effective predictive approaches.

In [50] we have considered the concept of high spatio-temporal correlated data and we have proposed a Belief Propagation (BP) algorithm to derive methods to drastically reduce the number of transmitted messages, by keeping an high accuracy in terms of global information.

Together with interference management approaches it is also important to figure out tools to support network operator for mitigation of the impact of failures on their infrastructures. The need of advanced Network Planning and Management Tool (NPMT) has been considered in [30].

7.7. Vehicular Networks

Participants: Nathalie Mitton, Valeria Loscri.

[27] studies the information delivery delay analysis for roadside unit deployment in a vehicular ad hoc network (VANET) with intermittent connectivity. A mathematical model is developed to describe the relationship between the average delay for delivering road condition information and the distance between two neighbor RSUs deployed along a road. The derived mathematical model considers a straight highway scenario where two RSUs are deployed at a distance without any direct connection and vehicles are sparsely distributed on the road with road condition information randomly generated between the two neighbor RSUs. Moreover, the model takes into account the vehicle speed, the vehicle density, the likelihood of an incident, and the distance between two RSUs. The effectiveness of the derived mathematical model is verified through simulation results. Given the information delivery delay constraint of a time-critical application, this model can be used to estimate the maximum distance allowed between two neighbor RSUs, which can provide a reference for the deployment of RSUs in such scenarios.

But Vehicular Networks can also convey social networks. In [53], we survey recent literature on Vehicular Social Networks that are a particular class of vehicular ad hoc networks, characterized by social aspects and features. Starting from this pillar, we investigate perspectives of next generation vehicles under the assumption of social networking for vehicular applications (i.e., safety and entertainment applications). This paper plays a role as a starting point about socially-inspired vehicles, and main related applications, as well as communication techniques. Vehicular communications can be considered as the "first social network for automobiles", since each driver can share data with other neighbors. As an instance, heavy traffic is a common occurrence in some areas on the roads (e.g., at intersections, taxi loading/unloading areas, and so on); as a consequence, roads become a popular social place for vehicles to connect to each other. Human factors are then involved in vehicular ad hoc networks, not only due to the safety related applications, but also for entertainment purpose. Social characteristics and human behavior largely impact on vehicular ad hoc networks, and this arises to the vehicular social networks, which are formed when vehicles (individuals) "socialize" and share common interests. This survey describes the main features of vehicular social networks, from novel emerging technologies to social aspects used for mobile applications, as well as main issues and challenges. Vehicular social networks are described as decentralized opportunistic communication networks formed among vehicles. They exploit mobility aspects, and basics of traditional social networks, in order to create novel approaches of message exchange through the detection of dynamic social structures. An overview of the main state-of-the-art on safety and entertainment applications relying on social networking solutions is also provided.

Cognitive Radio (CR) together with vehicular networks have been considered with an integrated and synergic perspective in [55], since CR technology is foreseen as a very effective tool to improve the communication efficiency in the context of vehicular networked systems.

7.8. Self-deployment and coverage

Participants: Nathalie Mitton, Tahiry Razafindralambo.

Controlled mobility in wireless sensor networks can provide many services. One of the most challenging one is coverage. Coverage can be needed either for monitoring control of specific area or point of interest or for deploying a communication network. This latter case is required for instance in post-disaster situations. In post-disaster scenarios, for example, after earthquakes or floods, the traditional communication infrastructure may be unavailable or seriously disrupted and overloaded. Therefore, rapidly deployable network solutions are needed to restore connectivity and provide assistance to users and first responders in the incident area. This work surveys the solutions proposed to address the deployment of a network without any a priori knowledge about the communication environment for critical communications. The design of such a network should also allow for quick, flexible, scalable, and resilient deployment with minimal human intervention. We survey this kind of approaches in [20].

In [13], we present a decentralized deployment algorithm for wireless mobile sensor networks focused on deployment Efficiency, connectivity Maintenance and network Reparation (EMR). We assume that a group of mobile sensors is placed in the area of interest to be covered, without any prior knowledge of the environment. The goal of the algorithm is to maximize the covered area and cope with sudden sensor failures. By relying on the locally available information regarding the environment and neighborhood, and without the need for any kind of synchronization in the network, each sensor iteratively chooses the next-step movement location so as to form a hexagonal lattice grid. Relying on the graph of wireless mobile sensors, we are able to provide the properties regarding the quality of coverage, the connectivity of the graph and the termination of the algorithm. We run extensive simulations to provide compactness properties of the deployment and evaluate the robustness against sensor failures. We show through the analysis and the simulations that EMR algorithm is robust to node failures and can restore the lattice grid. We also show that even after a failure, EMR algorithm call still provide a compact deployment in a reasonable time.

Routing a fleet of robots in a known surface is a complex problem. It consists in the determination of the exact trajectory each robot has to follow to collect information. The objective pursued in [38] is to maximize the exploration of the given surface. To ensure the robots can execute the mission in a collaborative manner, connectivity constraints are considered. These constraints guarantee that robots can communicate among each other and share the collected information. Moreover, the trajectories of the robots need to respect autonomy constraints.

7.9. Controlled Mobility for additional services

Participants: Nathalie Mitton, Valeria Loscri, Jean Cristanel Razafimandimby Anjalalaina.

Wireless sensor networks (WSNs) have been of very high interest for the research community since years, but most of the time, the mobility of nodes have been considered as an obstacle to overcome. In the contrary, in have tried to adopt another perspective and see it as an asset to exploit to provide additional services.

In [19], we leverage on the ability of mobile nodes to replace or recharge static sensors. Two main approaches can be identified that target this objective: either “recharging” or “replacing” the sensor nodes that are running out of energy. Of particular interest are solutions where mobile robots are used to execute the above mentioned tasks to automatically and autonomously maintain the WSN, thus reducing human intervention. Recently, the progress in wireless power transfer techniques has boosted research activities in the direction of battery recharging, with high expectations for its application to WSNs. Similarly, also sensor replacement techniques have been widely studied as a means to provide service continuity in the network. Objective of [19] is to investigate the limitations and the advantages of these two research directions. Key decision points must be identified for effectively supporting WSN self-maintenance: (i) which sensor nodes have to

be recharged/replaced; (ii) in which order the mobile robot is serving (i.e., recharging/replacing) the nodes and by following which path; (iii) how much energy is delivered to a sensor when recharged. The influence that a set of parameters, relative to both the sensors and the mobile robot, on the decisions will be considered. Centralized and distributed solutions are compared in terms of effectiveness in prolonging the network lifetime and in allowing network self-sustainability. The performance evaluation in a variety of scenarios and network settings offers the opportunity to draw conclusions and to discuss the boundaries for one technique being preferable to the other.

Mobility can also help for collecting data in wireless sensor networks [29]. The sensor data collection problem using data mules have been studied fairly extensively in the literature. However, in most of these studies, while the mule is mobile, all sensors are stationary. The objective of most of these studies is to minimize the time needed by the mule to collect data from all the sensors and return to the data collection point, from where it embarked on its data collection journey. The problem studied in this paper has two major differences with the earlier studies. First, in this study we assume that both the mule as well as the sensors are mobile. Second, we do not attempt to minimize the data collection time. Instead we minimize the number of mules that will be needed to collect data from all the sensors, subject to the constraint that the data collection process has to be completed within some pre-specified time. We show that the mule minimization problem is NP-Complete and provide a solution by first transforming it to a generalized version of the minimum flow problem in a network and then solving it optimally using Integer Linear Programming. Finally, we evaluate our algorithms through extensive simulation and present the results.

Internet of Robotic Things (IoRT) is a new concept introduced for the first time by ABI Research. Unlike the Internet of Things (IoT), IoRT provides an active sensorization and is considered as the new evolution of IoT. This new concept will bring new opportunities and challenges, while providing new business ideas for IoT and robotics' entrepreneurs.

In [46], we focus particularly on two issues: (i) connectivity maintenance among multiple IoRT robots, and (ii) their collective coverage.

We propose (i) IoRT-based, and (ii) a neural network control scheme to efficiently maintain the global connectivity among multiple mobile robots to a desired quality-of-service (QoS) level. The proposed approaches will try to find a trade-off between collective coverage and communication quality.

The IoT-based approach is based on the computation of the algebraic connectivity and the use of virtual force algorithm.

The neural network controller, in turn, is completely distributed and mimics perfectly the IoT-based approach. Results show that our approaches are efficient, in terms of convergence, connectivity, and energy consumption.

7.10. New and other communication paradigms

Participants: Nathalie Mitton, Valeria Loscri.

Interconnection and self-organized systems are normally populated with heterogeneous and different devices. The differences range from computational capabilities, storage size, etc. Instead of considering the heterogeneity as a limitation, it is possible to "turn it" as a primitive control of the system, in order to realize more robust and more resilient communication systems.

Based on those considerations, we have studied and analyzed the specific features of devices belonging to the category of micro-nano nodes that are however, required to interact with up-sized devices.

In order to improve the understanding of the behavior of micro/nano-sized devices, we have considered fundamental the analysis in specific applications and environment, where this kind of devices can be largely exploited, such as on/in-body networks applications.

Indeed, we retain that bio-medical applications can be advantaged by an effective and efficient communication and cooperation of devices deployed both on top of the body and inside it. Even if the research community recognizes a great importance to the study of interaction between the Human Immune System (HIS) and nano devices, this branch of research is in its infancy due to the major issue to model the HIS. A theoretical derivation of HIS and its interaction with a nanoparticulate system have been proposed in [15]. Some experimental results have been derived in [16], where specific parameters, e.g. temperature variations, Ph, etc. have been considered to establish the biocompatibility of TiO₂ particles with human tissues.

A step ahead in this direction has consisted in the consideration of alternative particles as potential information carriers always in the context of biological environments. In [40] we have studied *phonons* as information carriers, we have derived a channel modeling and evaluated the theoretical capacity. The main reasons for taking into consideration this type of nanoparticles are twofold. Firstly, phonons represent something that is naturally generated in a biological context with the application of a tolerable electromagnetic field and secondly they represent a straightforward way to implement nanomachines, since their native size.

7.11. Modelling and experimentations of interferences and other PHY effects

Participants: Nathalie Mitton, Valeria Loscri.

In the era of Internet of Things (IoT), the development of Wireless Sensor Networks (WSN) arises different challenges. Two of the main issues are electromagnetic interference and the lifetime of WSN nodes. In [48], we show and evaluate experimentally the relation between interference and energy consumption, which impacts the network lifetime. We present a platform based on commercially available low-cost hardware in order to evaluate the impact of electromagnetic interference in 2.4 GHz ISM band on energy consumption of WSN. The energy measurements are obtained separately from each electronic component in the node. Interference and energy measurements are conducted in an anechoic chamber and in an office-type lab environment. X-MAC protocol is chosen to manage the Radio Duty Cycle of the nodes and its energy performance is evaluated. The energy consumption transmitter nodes is analyzed particularly in this work. Moreover, this energy consumption has been quantified and differentiated according to the number of (re-)transmissions carried out by the transmitter as well as the number of ACK packets sent by the receiver for a single packet. Finally, we use a model of real battery to calculate the lifetime of the node for operation within different interference level zones. This study lays the basis for further design rules of communication protocols and development of WSNs.

In [49], we propose a WSN architecture for wild animal monitoring. The key requirements of the system are long range transmissions and low power consumption. Indeed, the animals could be spread over vast areas. Kruger National Park in South Africa (19485 km²) is the potential zone of implementation of the network. On the other hand, size and weight limitations of wearable devices must be respected, which limits the size and capacity of battery. Moreover, battery replacement is a difficult and expensive process. So, low energy consumption is essential to extend the network lifetime. Some animal tracking projects [3] use GSM to transmit collected data to insure the coverage over a large area. However, high energy consumption of GSM and lack of coverage of the deployment area do not meet the essential requirements of the application. LoRa technology provides both long range transmissions and low power operation. This technology could be an appropriate solution for PREDNET project. The contribution of this work is multiple: 1) we defined communication parameters of LoRa radio for PREDNET WSN; 2) we performed radio propagation simulation for chosen parameters to estimate the coverage area for both urban and wilderness (rural) scenarios; 3) we confirmed the propagation simulations with range tests; 4) we measured experimentally the Packet Error Rate (PER) of transmissions.

Terahertz frequency band is an emerging research area related to nano-scale communications. In this frequency range, specific features can provide the possibility to overcome the issues related to the spectrum scarcity and capacity limitation.

Apart high molecular absorption, and very high reflection loss that represent main phenomena in THz band, we can derive the characteristics of the channel affected by chirality effects occurring in the propagation medium, specifically , in the case where a Giant Optical Activity is present. This effect is typical of the so-called chiral-metamaterials in (4-10) THz band, and is of stimulating interest particularly for millimeter wireless communications.

In [51], [25], we analyze the behavior of specific parameters of a chiral-metamaterial, like the relative electrical permittivity, magnetic permeability and chirality coefficients, and from that we derive the channel behavior both for Line-of-Sight and No Line-of-Sight propagations. We notice the presence of spectral windows, due to peaks of resonance of chiral parameter.

Finally, performances of the chirality-affected channel have been assessed in terms of (i) channel capacity, (ii) propagation delay, and (iii) coherence band-width, for different distances.

Thanks to the exploitation of frequencies in the interval ranging from 0.06 to 10 THz, it is envisioned the possibility to overcome the issues related to the spectrum scarcity and capacity limitation. On the other hand, the design of new channel models, able to capture the inherent features of the phenomenons related with this specific field is of paramount importance. Very high molecular absorption, and very high reflection loss are peculiarities phenomenons that need to be included in these models. In [26], we present a full-wave propagation model of the electromagnetic field that propagates in the THz band both for Line-of-Sight and Non-Line-of-Sight propagation models. In the full-wave model, we also introduce the chirality effects occurring in the propagation medium, i.e., a chiral metamaterial.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

- Evolution

Participants: Gabriele Sabatino, Nathalie Mitton [correspondant].

This collaboration aims to set up a full RFID system on the basis of AspireRFID middleware and pre-existing RFID modules issued from FUN research in the Evolution company facility and to integrate them with their IS.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. Tracaverre

Participants: Nathalie Mitton [correspondant], Gabriele Sabatino.

Title: Tracaverre

Type: FUI

Duration: November 2012 - Dec 2016

Coordinator: Saver Glass

Others partners: Inria FUN IEMN Courbon Camus La Grande Marque LIRIS DISP

Tracaverre studies the use of RFID for traceability of prestigious bottles. Tracaverre has yielded to the implementation of the T-Scan software.

9.1.2. StoreConnect

Participants: Nathalie Mitton [correspondant], Valeria Loscri.

Title: StoreConnect

Type: FUI

Duration: September 2016 - October 2018

Coordinator: NEOSSENSYS

Others partners: Inria FUN, SPIRALS and STARS, TeVolys, Ubudu, Smile, STIME, Leroy Merlin

The aim of StoreConnect is to provide French large retailers with efficient and powerful tools in the in-store customer interaction.

9.1.3. PIPA

Participants: Nathalie Mitton [correspondant], Farouk Mezghani, Cristina Cano Bastidas.

Title: Partager de l'Info PARTout à bas coût

Type: Chercheur citoyen

Duration: Dec 2015 - Dec 2017

Coordinator: Inria FUN

Others partners: SpotTrotter

PIPA project aims to provide an innovative low cost solution to share information in places where communication infrastructure are lacking, insufficient or not adapted, going beyond technical, economical or political limitations.

9.2. National Initiatives

9.2.1. Inria Project Lab

9.2.1.1. CityLab@Inria

Participants: Valeria Loscri, Abdoul Aziz Mbacke, Nathalie Mitton [correspondant].

- Title: CityLab@Inria
- Type: IPL
- Duration: 2015 - 2019
- Coordinator: Valerie Issarny
- CityLab@Inria studies ICT solutions toward smart cities that promote both social and environmental sustainability. A strong emphasis of the Lab is on the undertaking of a multi-disciplinary research program through the integration of relevant scientific and technology studies, from sensing up to analytics and advanced applications, so as to actually enact the foreseen smart city Systems of Systems. Obviously, running urban-scale experiments is a central concern of the Lab, so that we are able to confront proposed approaches to actual settings. The Lab's research leverages relevant effort within Inria project-teams that is further revisited as well as integrated to meet the challenges of smart cities. Research themes span: energy-efficient wireless communication protocols, urban-scale social and physical sensing, privacy by design, cloud-based urban data management, data assimilation, visual analysis, and urban system software engineering. In addition, CityLab Inria research builds upon collaborative effort at the International level, and especially collaboration in the context of the Inria SiliconValley program. This project has yield to the set up of a full course on Smart Cities via a MOOC.

9.2.2. ADT

9.2.2.1. RFunID

Participants: Clement Fumey, Nathalie Mitton [correspondant], Julien Vandaele.

Duration: September 2015 - August 2017

Coordinator: Inria FUN

The purpose of this project is to deploy a large scale experimental RFID platform that enables remote programming of RFID scenario on heterogeneous devices.

9.2.2.2. ARUNTA

Participants: Emilio Compagnone, Valeria Loscri [correspondant], Julien Vandaele.

Title: Arduino-based Robots for Ubiquitous Network (ARUNTA)

Type: ADT

Duration: September 2014 - August 2016

Coordinator: Inria FUN

Abstract: This ADT focuses on the use of Arduino, an open-source electronics prototyping platform, really flexible and easy-to-use [1] to allow a fleet of robots to perform specific tasks. The goal of the ADT is to make experiments on Arduino-based robotic platforms, by implementing two robot cooperation algorithms that have been already tested through simulation tools. In order to extend the users' community and to allow more people to benefit from this research on robot cooperation, this ADT will output a tutorial and a test-bed will be developed. Moreover, the final project will be shared with the Arduino community and every interested user.

9.2.3. Equipements d'Excellence

9.2.3.1. FIT

Participants: Nathalie Mitton [correspondant], Julien Vandaele.

Title: Future Internet of Things

Type: EquipEx

Duration: March 2010 - December 2019

Coordinator: UPMC

See also: <http://fit-equipex.fr/>

Abstract: FIT (Future Internet of Things) aims to develop an experimental facility, a federated and competitive infrastructure with international visibility and a broad panel of customers. It will provide this facility with a set of complementary components that enable experimentation on innovative services for academic and industrial users. The project will give 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 is one of 52 winning projects from the first wave of the French Ministry of Higher Education and Research's "Equipements d'Excellence" (Equipex) research grant program. Coordinated by Professor Serge Fdida of UPMC Sorbonne Universités and running over a nine-year period, the project will benefit from a 5.8 million euro grant from the French government. This project has yield to several publications in 2016: [44], [43].

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

9.3.1.1. VITAL

Participants: Salvatore Guzzo Bonifacio, Valeria Loscri, Nathalie Mitton [correspondant], Riccardo Petrolo.

Title: Virtualized programmable InTerFAces for innovative cost-effective IoT depLoYments in smart cities

Programm: FP7

Duration: September 2013 - December 2016

Coordinator: National University of Ireland Galway (NUIG)

Partners:

Research and Education Laboratory in Information Technologies (Greece)

Atos Spain (Spain)

Camden Town Center (United Kingdom)

Images & Co (United Kingdom)

Istanbul Metropolitan Municipality (Turkey)

Istanbul Teknik Universitesi (Turkey)

National University of Ireland, Galway (Ireland)

Santer Reply Spa (Italy)

Singularlogic Anonymi Etairia Pliroforiakon Sistimaton Kai Efarmogon Pliroforikis (Greece)

Inria contact: Nathalie Mitton

Internet-of-Things (IoT) applications are currently based on multiple architectures, standards and platforms, which have led to a highly fragmented IoT landscape. This fragmentation is evident in the area of smart cities, which typically comprise several technological silos (i.e. IoT systems that have been developed and deployed independently). Nowadays there is a pressing need to remove these silos in order to allow cities to share data across systems and coordinate processes across domains, thereby essentially improving sustainability and quality of life. In response to this need, VITAL will realize a radical shift in the development, deployment and operation of IoT applications, through introducing an abstract virtualized digital layer that will operate across multiple IoT architectures, platforms and business contexts. Specifically, VITAL will provide platform and business context agnostic access to Internet-Connected-Objects (ICO). Moreover, it will research virtualized filtering, complex event processing (CEP) and business process management mechanisms, which will be operational over a variety of IoT architectures/ecosystems. The mechanisms will compromise the diverse characteristics of the underlying ecosystems, thereby boosting interoperability at the technical and business levels. VITAL will also provide development and governance tools, which will leverage the project's interfaces for virtualized access to ICOs. VITAL will allow solution providers to (re)use a wider range of data steams, thereby increasing the scope of potential applications. It will also enable a more connected/integrated approach to smart city applications development, which will be validated in realistic deployments in London and Istanbul. The partners will contribute and adapt a host of readily available urban infrastructures, IoT platforms and novel IoT applications, which will ease the accomplishment of the project's goals based on an optimal value for EC money. Publications in 2016 in the framework of this project are: [21], [44], [43], [42].

9.3.1.2. VESSEDIA

Participant: Simon Duquennoy [correspondant].

Title: VERIFICATION ENGINEERING OF SAFETY AND SECURITY CRITICAL DYNAMIC INDUSTRIAL APPLICATIONS

Programm: H2020

Duration: January 2017 - Dec. 2019

TECHNIKON FORSCHUNGS UND PLANUNGSGESELLSCHAFT MBH (TEC) The VESSEDIA project will bring safety and security to many new software applications and devices. In the fast evolving world we live in, the Internet has brought many benefits to individuals, organisations and industries. With the capabilities offered now (such as IPv6) to connect billions of devices and therefore humans together, the Internet brings new threats to the software developers and VESSEDIA will allow connected applications to be safe and secure. VESSEDIA proposes to enhance and scale up modern software analysis tools, namely the mostly open-source Frama-C Analysis platform, to allow developers to benefit rapidly from them when developing connected applications. At the forefront of connected applications is the IoT, whose growth is exponential and whose security risks are real (for instance in hacked smart phones). VESSEDIA will take this domain as a target for demonstrating the benefits of using our tools on connected applications. VESSEDIA will tackle this challenge by 1) developing a methodology that allows to adopt and use source code analysis tools efficiently and produce similar benefits than already achieved for highly-critical applications (i.e. an exhaustive analysis and extraction of faults), 2) enhancing the Frama-C toolbox to enable efficient and fast implementation, 3) demonstrating the new toolbox capabilities on typical IoT (Internet of Things) applications including an IoT Operating System (Contiki), 4) developing a standardisation plan for generalizing the use of the toolbox, 5) contributing to the Common Criteria certification process, and 6) defining a label "Verified in Europe" for validating software products with European technologies such as Frama-C.

9.4. International Initiatives

9.4.1. Inria International Labs

9.4.1.1. PREDNET

Participants: Simon Duquennoy, Nathalie Mitton [correspondant], Viktor Toldov, Julien Vandaele.

Title: Predator network

Type: LIRIMA with Stellenbosch University, South Africa

Duration: January 2013 - December 2016

See also: <https://www.inria.fr/prednet/en/>

Abstract: PREDNET (PREDator adhoc NETwork) proposes to do research on the most suitable topology and subsequent deployment of a wireless sensor network for sparsely populated outlying rural and wilderness areas, for effective monitoring and protection of resources and ecosystems. This collaboration gave birth to joint project submission, joint conference organization and several publications, among them for 2016 [47], [48], [48], [49].

9.4.2. Inria Associate Teams Not Involved in an Inria International Labs

9.4.2.1. DepIoT

Participants: Simon Duquennoy [correspondant], Nathalie Mitton.

Title: DepIoT: Coexistence and Security for Dependable Internet of Things

Type: North-European Inria Associate Team with SICS, Sweden

Duration: Sept 2016 - August 2018

Abstract: In order to foster the adoption of IoT technologies, dependability must be guaranteed. We will tackle this challenge by ensuring operation even in the presence of other networks sharing the same frequency band (coexistence) and by enabling a secure communication.

9.4.3. Inria International Partners

9.4.3.1. Declared Inria International Partners

Università Mediterranea di Reggio Calabria (UNIC) (Italy) Objective of this collaboration is the design of an innovative architecture that enables autonomic and decentralized fruition of the services offered by the network of smart objects in many heterogeneous and dynamic environments, in a way that is independent of the network topology, reliable and flexible. The result is an 'ecosystem' of objects, self-organized and self-sustained, capable of making data and services available to the users wherever and whenever required, thus supporting the fruition of an 'augmented' reality thanks to a new environmental and social awareness. This collaboration has allowed students and researchers exchanges and joint publications, among them for 2016: [20], [19].

9.4.3.2. Informal International Partners

Southern University, China

The purpose of this collaboration is to study the green (or energy-efficient) communication problem in vehicular ad hoc networks (VANETs) and the application of vehicular network communication in green transportation. In this framework, Nathalie Mitton visited the Nanjing University. It gave birth to joint project submission, joint conference organization (UIC 2016) and joint publications, one in 2016 [27].

Arun Sen from Arizona State University, USA

The purpose of this collaboration is to study the joint scheduling and trajectory of RFID readers in a mobile environment. In this framework, Arun Sen visited the FUN team for 6 months in 2015 and in July 2016. It gave birth to joint project submission, joint conference submission and joint publications, among them in 2016 [30], [29].

Anna-Maria Vegni from Roma Tre University, Italy

The purpose of this collaboration is to study alternative communication paradigms and investigate their limitations and different effects on performances. In this framework, joint publications have been obtained, among them in 2016 [51], [26], [53], [50], [46], [40], [16], [55], [15], [45], [25].

9.4.3.3. PhD co-supervision

Participants: Nathalie Mitton [correspondant], Mouna Masmoudi.

Since January 2013, Nathalie Mitton co-supervises Mouna Rekik as a PhD student with Pr Zied Chtourou from Université de Sfax, Tunisia. Her topic is about swarm intelligence based multi-path geographic routing for wireless sensor and actuator networks.

This work has led to the following publications in 2016: [23]. Mouna defended her PhD on July 26th 2016.

Since 2014, Simon Duquennoy co-supervised Anwar Hithnawi as a PhD student with Pr Friedemann Mattern from ETH Zurich, Sweden. Her research is on low-power wireless systems coexistence, and mitigation of cross-technology interference. This work has led to the following publications in 2016: [39]. Anwar defended her PhD on November 8, 2016.

9.4.4. Participation in Other International Programs

9.4.4.1. CROMO

Participants: Valeria Loscri, Nathalie Mitton [correspondant], Riccardo Petrolo, Abdoul Aziz Mbacke.

Title: Crowd Data In the mobile cloud

Duration: January 2015 - December 2019

CroMo (Crowd Data In the mobile cloud) is a submission to the CAPES-COFECUB project call lead by Inria from the French side and University of Rio de Janeiro from Brazilian Side. Other partner institutions are Université Pierre et Marie Curie and Université de la Rochelle.

Mobile cloud computing is an emerging paradigm to improve the quality of mobile applications by transferring part of the computational tasks to the resource-rich cloud. The multitude data sources combined with the known difficulties of wireless communications represent an important issue for mobile cloud computing. Therefore, the additional computational power added by the cloud has to deal with the constraints of the wireless medium. One could imagine a situation where different sensors collect data and require intensive computation. This data must be transmitted at high rates before becoming stale. In this case, the network becomes the main bottleneck, not the processing power or storage size. To circumvent this issue, different strategies can be envisioned. As usual alternatives, wireless data rates must be increased or the amount of data sent to the cloud must be reduced. CROMO tackles challenges from all these three components of the mobile clouds (data generation, collect and processing) to then integrate them as a whole enhanced mobile cloud with improved network performances in terms of delay, energy consumption, availability, and reliability.

In this context, joint exchanges and crossed visits have been done (Aziz went to Rio, Dianne went to Lille). The project yield to several publications such as [35], [36], [37].

9.5. International Research Visitors

9.5.1. Visits of International Scientists

9.5.1.1. Senior researchers

Several researchers have visited our group in 2016, mainly from our partner universities but not only:

- Zied Chtourou, Univ. Sfax, Tunisia, July 2016
- Arun Sen, Arizona State University, USA, July 2016
- Ahmet Sekercioglu, Monash University, Australia, July 2016
- Riaan Wolhuter, Univ. Stellenbosch, South Africa, July 2016
- Anwar Hithnawi, ETH Zurich, Switzerland, March 2016
- Hossein Shafagh, ETH Zurich, Switzerland, March 2016
- Cédric Chauvenet from ERDF, May 2016

9.5.1.2. Internships

Other students have visited us from our partner universities in the framework of the joint project we run together. This is the case for William Pretorius (2 months) who came from Stellenbosch university, South Africa, in the framework of the PredNET program and Rahul Vyas from IIIT Allahabad, India (2 months).

9.5.2. Visits to International Teams

- Riccardo Petrolo visited Ericsson group in Finland in April 2016.
- Nathalie Mitton visited Southeast university in Nanjing, China in June 2016.
- Simon Duquennoy visited SICS in Sweden in September 2016 and May 2016.
- Aziz Mbacke visited UFRJ in Brazil in November 2016.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

- Nathalie Mitton is a member of the Steering committee of CIoT.

- Nathalie Mitton is general chair for AdHocNow 2016 and InterIoT 2016 and symposium chair of Wireless Ad hoc and Sensor Networks symposium ICNC 2017.
- Valeria Loscri is TPC chair for BODYNETS 2016, general co-chairs for PASC 2016, TPC co-chair for CoWPER 2016, TPC chair for the IoT day 2016
- Mouna Rekik was publicity chair for AdHocNet 2016.
- Aziz Mbacke is publicity chair for AdHocNow 2016.
- Riccardo Petrolo was web chair for AdHocNow 2016.
- Jean Razafimandimby Anjalalaina, was Publicity Chair for IoTIP 2016.

10.1.1.2. Member of the Organizing Committees

- the next CapTronic workshop on Factories of the future. Attendees : industries, \approx 50 participants
- the International Conference on Ad Hoc Networks and Wireless (AdHoc-Now) from July 4th to July 6th (<https://project.inria.fr/AdHocNow2016/>), Attendees : academics, international \approx 50 participants
- the Rescom days in January 12th and 13th, Attendees : academics, french-speaking \approx 70 participants

10.1.2. Scientific Events Selection

10.1.2.1. Chair of Conference Program Committees

- Valeria Loscri is co-program chairs for AdHocNow 2016.
- Nathalie Mitton is/was (co-)program chair of the RESCOM community days in January 2016, for AdHocNow 2016, UIC 2016, VTC-Spring 2016, IoTIP 2016, ICNC 2016 and CSE 2016. She is co-program chair for WSCP 2017, VTC2017 and SWC 2017.

10.1.2.2. Member of the Conference Program Committees

- Valeria Loscri is/was in the Technical Program Committee (TPC) of MoWNet'16, IDCS 2016, HPCC 2016, WiMob 2016, ICARSC 2016, GIoTS 2017, MoWNet 2017, WiMob 2017, NanoComm 2017.
- Nathalie Mitton is/was in the Technical Program Committee (TPC) ICC 2016, SmartComp 2016, GlobeCom 2016, WPMC2016, PASC 2016, Wisarn 2016, CCNC 2017, VTC 2017
- Simon Duquennoy is TPC member of EWSN 2016 (and 2017), IEEE DCoSS 2016 (and 2017), IEEE MASS 2016, InterIoT 2016, UIC 2016

10.1.3. Journal

- Valeria Loscri is Co-editor in the Special Issue on Smart Wireless Access Networks and Systems For Smart Cities, Elsevier Ad Hoc Networks.
- Valeria Loscri is Co-editor for the book MIoT2015, Management of Cyber Physical Objects in the Future Internet of Things on behalf of Springer.
- Valeria Loscri is Co-editor for the book Vehicular Social Networks, on behalf of CRC Press Taylor and Francis Group.
- Valeria Loscri is a member of the 'Research Group on IoT Communications and Networking Infrastructure' at ComSoc Communities.

10.1.3.1. Member of the Editorial Boards

- Nathalie Mitton is editorial board members of AHSWN since 2011.
- Nathalie Mitton is editorial board member of Adhoc Networks since 2012.
- Nathalie Mitton is editorial board member of IET-WSS since 2013.
- Nathalie Mitton is editorial board member of ComSoc MMTTC e-letter since 2014.
- Nathalie Mitton is editorial board member of Wiley Transactions Emerging Telecommunications Technologies since 2016.

- Nathalie Mitton is editorial board member of Wireless Communications and Mobile Computing since 2016.
- Valeria Loscri is editorial board member of International Journal of Advanced Robotic Systems since 2016

10.1.4. Invited Talks

- Nathalie Mitton was invited speaker at CNRS Josy Days in Paris in October 2016
- Nathalie Mitton was invited speaker at Smyle Workshop at EPFL in Neuchatel, Switzerland, in September 2016
- Riccardo Petrolo was invited speaker at Rice University in Houston, USA in September 2016
- Nathalie Mitton was invited speaker at 4th International Workshop on Next Generation Green Wireless Networks (NextGWiN 2016) in Dublin, Ireland, September 2016
- Nathalie Mitton was invited speaker at Southeast University Seminar in Nanjing, China in June 2016
- Valeria Loscri was invited speaker at BIS days in Paris, June 2016
- Nathalie Mitton was invited speaker at 10th European eAccessibility Forum "e-Accessibility in a Connected World in Paris, May 2016
- Nathalie Mitton was invited speaker at UCN@Sophia Labex seminar Sophia Antipolis, April 2016
- Nathalie Mitton was invited speaker at "US-EU Workshop on the Next Generation Internet", Los Angeles, March 2016
- Nathalie Mitton was invited speaker at "IoT day Paris Descartes" on March 2016
- Valeria Loscri and Nathalie Mitton were invited speakers at JEAJ days in Lille on February 2016
- Simon Duquenoy was invited speaker at Bristol for the Sphere IRC project, in November 2016

10.1.5. Leadership within the Scientific Community

Nathalie Mitton is a member of the Steering Committee of the GDR Rescom.

10.1.6. Scientific Expertise

Nathalie Mitton is an elected member of the evaluation community of Inria. She has acted as a reviewer for ANRT and ANR project submissions. She is also member of the scientific committees of the competitiveness cluster of MATIKEN and for CITC (International Contactless Technologies Center).

Valeria Loscri is Scientific European Responsible for Inria Lille - Nord Europe. She has been reviewer in the context of 2017 Air Force Young Investigator Research Program. *Simon*

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

E-learning

Mooc, Nathalie Mitton, "Villes intelligentes : défis technologiques et sociétaux" , 5-week mooc by the IPL CityLab@Inria team, FUN, Inria, to open in January 2016

Master : Valeria Loscri, Objets Communicants, 24h (Mineure Habitat Intelligent), Ecole des Mines de Douai, France.

Master : Nathalie Mitton, Wireless sensor networks, 16h eqTD (Master MINT), Université Lille 1 and Telecom Lille 1, France

Bsc: Nathalie Mitton, Contactless technologies, 20h eqTD, Université de Valenciennes, France

Bsc: Farouk Mezghani, Contactless technologies, 20h eqTD, Université de Valenciennes, France

BSC: Riccardo Petrolo, Réseaux Informatique, 36h TP and TD (Licence Info), Université Lille 1, France

BSC: Riccardo Petrolo, Technologies du Web, 36h TP and TD (Licence 1), Université Lille 1, France

Master : Viktor Toldov, Systèmes Numériques (VHDL), 6h eqTD (Formation d'ingénieur), Télécom Lille, France

Licence : Jean Razafimandimby, Algorithms and Programming 1, 32h TP and TD, Université Lille 1, France

Licence : Jean Razafimandimby, Algorithms and Programming 2, 32h TP and TD, Université Lille 1, France

10.2.2. Supervision

PhD defended on July 26th 2016: Mouna Rekik, geographic multi path routing protocol based on swarm intelligence for wireless sensor and actuator networks in the context of Smart Grids, co-supervision Université Lille 1 and University of Sfax (Tunisia), 2013-2017, Nathalie Mitton and Zied Chtourou

PhD defended on Oct 25th 2016: Riccardo Petrolo, Internet of Things and Smart Cities, Université Lille 1, 2013-2016, Nathalie Mitton and Valeria Loscri

PhD in progress: Viktor Toldov, : Interférence et consommation dans les réseaux de capteurs, Université Lille 1, 2013-2016, Nathalie Mitton and Laurent Clavier

PhD in progress: Jean Razafimandimby, Distributed Cooperation and Communication among Heterogeneous Devices, Université Lille 1, 2014-2017, Nathalie Mitton and Valeria Loscri

PhD in progress: Aziz Mbacke, Smart Deployment of heterogeneous sensors and RFID in a Smart City, Université Lille 1, 2015-2018, Nathalie Mitton and Hervé Rivano (Urbanet)

PhD in progress: Jad Nassar, Ubiquitous networks for smart grids, Université Lille 1, 2015-2018, Nathalie Mitton and Nicolas Gouvy (HEI)

10.2.3. Juries

- PhD/HDR committees :
 - Simon Duquennoy was a member of the PhD defense committee of
 - * Mathieu Michel, University Mons Belgium, September 2016
 - * Anwar Hithnawi, ETH Zurich in November 2016.
 - Valeria Loscri was a member of the PhD defense committee of Riad Mazloun, University Paris 6, December 2016.
 - Valeria Loscri was reviewer of the the following PhD thesis: Orazio Briante, Università Mediterranea di Reggio Calabria, May 2016.
 - Nathalie Mitton is/was reviewer of the following PhD thesis:
 - * Remy Leone, UPMC, June 2016,
 - * Quentin Bramas, UPMC, October 2016,
 - * Laurent Reynaud, Univ. Lyon 1, March 2017.
 - Nathalie Mitton was a member of the HDR defense committee of Nadjib AIT SAADI, University of Paris-Est Creteil Val de Marne (UPEC) 18 July 2016.
- Researcher selection committees :
 - Valeria Loscri was member of the Inria CR2 Lille competition selection committee.
 - Nathalie Mitton was member of the Inria CR2 Grenoble competition selection committee.
 - Nathalie Mitton was member of the Inria Research Grant Position selection committee.
 - Nathalie Mitton was member of the Assistant Professor (MdC) at Universités de Valenciennes, Rennes et de Lorraine, Institut Mines Telecom ParisTech competition selection committees.

- Nathalie Mitton is a member of the scientific committee of "Convergences du Droit et du Numérique".
- Valeria Loscri is a member of the committee of "Journée Nationale de l'Internet des Objets".

10.3. Popularization

- Tahiry Razafindralambo and Simon Duquennoy gave a talk for 13-45 in April 2016
- Emilio Compagnone gave a talk for 13-45 in May 2016
- Cristina Cano gave a talk at "30 min de Sciences" in May 2016
- Emilio Compagnone and Valeria Loscri gave a talk and a demo at Robotic Day at Euratechnologies in July 2016
- Nathalie Mitton, Cristina Cano and Viktor Toldov gave talks at IoTWeek by CITC on June 2016
- Nathalie Mitton gave a talk at NormaFret by i-Trans competitiveness cluster in September 2016
- Aziz Mbacke, Jad Nassar and Julien Vandaele gave some talks in high schools for the "Fête de la Science" in October 2016
- Nathalie Mitton co-authored popularization articles in La main à la pâte (to be published in January 2017), white paper on e-accessibility for BrailleNet/G3ict and an article in *Big Data à découvert* by CNRS edition.

11. Bibliography

Major publications by the team in recent years

- [1] V. LOSCRÍ, L. MATEKOVITS, I. PETER, A. M. VEGNI. *In-body Network Biomedical Applications: from Modeling to Experimentation*, in "IEEE Transactions on NanoBioscience", 2016 [DOI : 10.1109/TNB.2016.2521386], <https://hal.inria.fr/hal-01262020>
- [2] F. MANGANO, S. DUQUENNOY, N. KOSMATOV. *Formal Verification of a Memory Allocation Module of Contiki with Frama-C: a Case Study*, in "CRiSIS 2016 - 11th International Conference on Risks and Security of Internet and Systems", Roscoff, France, September 2016, <https://hal.inria.fr/hal-01351142>
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- [4] L. MILITANO, M. ERDELJ, A. MOLINARO, N. MITTON, A. IERA. *Recharging vs. Replacing Sensor Nodes Using Mobile Robots for Network Maintenance*, in "Telecommunications Systems", February 2016, <https://hal.inria.fr/hal-01242236>
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- [6] R. PETROLO, V. LOSCRI, N. MITTON. *Confident-based Adaptable Connected objects discovery to HArmonize smart City Applications*, in "Proceedings of WD - IFIP Wireless Days", Toulouse, France, March 2016, <https://hal.inria.fr/hal-01269633>

- [7] C. RAZAFIMANDIMBY, V. LOSCRI, A. M. VEGNI. *A neural network and IoT-based scheme for performance assessment in Internet of Robotic Things*, in "I4T - 1st International Workshop on Interoperability, Integration, and Interconnection of Internet of Things Systems", Berlin, Germany, April 2016, <https://hal.inria.fr/hal-01261842>
- [8] V. TOLDOV, L. CLAVIER, V. LOSCRÍ, N. MITTON. *A Thompson Sampling Approach to Channel Exploration-Exploitation Problem in Multihop Cognitive Radio Networks*, in "27th annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)", Valencia, Spain, September 2016, <https://hal.inria.fr/hal-01355002>
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- [10] A. M. VEGNI, V. LOSCRÍ, A. NERI, M. LEO. *A Bayesian Packet Sharing Approach for Noisy IoT Scenarios*, in "1st International Workshop on Interoperability, Integration, and Interconnection of Internet of Things Systems (I4T 2016)", Berlin, Germany, April 2016, <https://hal.inria.fr/hal-01262024>

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- [11] R. PETROLO. *Semantic-based discovery and integration of heterogeneous things in a Smart City environment*, University of Lille 1, October 2016, <https://hal.inria.fr/tel-01403844>
- [12] M. REKIK. *Geographical multipath routing based on swarm intelligence for wireless sensors and actuators networks: Application to Smart Grids*, Université Lille 1 ; Université de Sfax, July 2016, <https://hal.inria.fr/tel-01370723>

Articles in International Peer-Reviewed Journals

- [13] M. ERDELJ, N. MITTON, T. RAZAFINDRALAMBO. *Robust Wireless Sensor Network Deployment*, in "Discrete Mathematics and Theoretical Computer Science", 2016, vol. 17, n^o 3, pp. 105-130, <https://hal.inria.fr/hal-01296574>
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- [15] V. LOSCRI, A. M. VEGNI, G. FORTINO. *On the Interaction between a Nanoparticulate System and the Human Body in Body Area Nanonetworks*, in "Micromachines", 2016, vol. 6, n^o 9, pp. 1213-1235 [DOI : 10.3390/MI6091213], <https://hal.inria.fr/hal-01188280>
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- [22] T. RAZAFINDRALAMBO, M. ERDELJ, D. ZORBAS, E. NATALIZIO. *Spread and shrink: Point of interest discovery and coverage with mobile wireless sensors*, in "Journal of Parallel and Distributed Computing", November 2016 [DOI : 10.1016/J.JPDC.2016.09.003], <https://hal.inria.fr/hal-01406492>
- [23] M. REKIK, Z. CHTOUROU, N. MITTON, A. ATIEH. *Geographic routing protocol for the deployment of virtual power plant within the smart grid*, in "Sustainable Cities and Society", 2016 [DOI : 10.1016/J.SCS.2015.12.003], <https://hal.inria.fr/hal-01252686>
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