Activity Report 2018

Project-Team EVA

Wireless Networking for Evolving & Adaptive Applications

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Creation of the Team: 2015 April 01, updated into Project-Team: 2016 May 01

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1. Team, Visitors, External Collaborators

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2. Overall Objectives

2.1. Overall Objectives

It is forecast that the vast majority of Internet connections will be wireless. The EVA project grasps this opportunity and focuses on wireless communication. EVA tackles challenges related to providing efficient communication in wireless networks and, more generally, in all networks that are not already organized when set up, and consequently need to evolve and spontaneously find a match between application requirements and the environment. These networks can use opportunistic and/or collaborative communication schemes. They can evolve through optimization and self-learning techniques. Every effort is made to ensure that the results provided by EVA have the greatest possible impact through standardization. The miniaturization and ubiquitous nature of computing devices has opened the way to the deployment of a new generation of wireless (sensor) networks. These networks are central to the work in EVA, as EVA focuses on such crucial issues as power conservation, connectivity, determinism, reliability and latency. Wireless Sensor Network (WSN) deployments are also be a new key subject, especially for emergency situations (e.g. after a disaster). Industrial process automation and environmental monitoring are considered in greater depth.

3. Research Program

3.1. Pitch

Designing Tomorrow's Internet of (Important) Things

Inria-EVA is a leading research team in low-power wireless communications. The team pushes the limits of low-power wireless mesh networking by applying them to critical applications such as industrial control loops, with harsh reliability, scalability, security and energy constraints. Grounded in real-world use cases and experimentation, EVA co-chairs the IETF 6TiSCH standardization working group, co-leads Berkeley's OpenWSN project and works extensively with Analog Devices' SmartMesh IP networks. Inria-EVA is the birthplace of the Wattson Elements startup and the Falco solution. The team is associated with Prof. Glaser's (UC Berkeley) and Prof. Kerkez (U. Michigan) through the REALMS associate research team, and with OpenMote through a long-standing Memorandum of Understanding.

3.2. Physical Layer

We study how advanced physical layers can be used in low-power wireless networks. For instance, collaborative techniques such as multiple antennas (e.g. Massive MIMO technology) can improve communication efficiency. The core idea is to use massive network densification by drastically increasing the number of sensors in a given area in a Time Division Duplex (TDD) mode with time reversal. The first period allows the sensors to estimate the channel state and, after time reversal, the second period is to transmit the data sensed. Other techniques, such as interference cancellation, are also possible.

3.3. Wireless Access

Medium sharing in wireless systems has received substantial attention throughout the last decade. HiPER-COM2 has provided models to compare TDMA and CSMA. HiPERCOM2 has also studied how network nodes must be positioned to optimize the global throughput.

EVA pursues modeling tasks to compare access protocols, including multi-carrier access, adaptive CSMA (particularly in VANETs), as well as directional and multiple antennas. There is a strong need for determinism in industrial networks. The EVA team focuses particularly on scheduled medium access in the context of deterministic industrial networks; this involves optimizing the joint time slot and channel assignment. Distributed approaches are considered, and the EVA team determines their limits in terms of reliability, latency and throughput. Furthermore, adaptivity to application or environment changes are taken into account.

3.4. Coexistence of Wireless Technologies

Wireless technologies such as cellular, low-power mesh networks, (Low-Power) WiFi, and Bluetooth (low-energy) can reasonably claim to fit the requirements of the IoT. Each, however, uses different trade-offs between reliability, energy consumption and throughput. The EVA team will study the limits of each technology, and will develop clear criteria to evaluate which technology is best suited to a particular set of constraints.

Coexistence between these different technologies (or different deployments of the same technology in a common radio space) is a valid point of concern.

The EVA team aims at studying such coexistence, and, where necessary, propose techniques to improve it. Where applicable, the techniques will be put forward for standardization. Multiple technologies can also function in a symbiotic way.

For example, to improve the quality of experience provided to end users, a wireless mesh network can transport sensor and actuator data in place of a cellular network, when and where cellular connectivity is poor.

The EVA team will study how and when different technologies can complement one another. A specific example of a collaborative approach is Cognitive Radio Sensor Networks (CRSN).

3.5. Energy-Efficiency and Determinism

Reducing the energy consumption of low-power wireless devices remains a challenging task. The overall energy budget of a system can be reduced by using less power-hungry chips, and significant research is being done in that direction. That being said, power consumption is mostly influenced by the algorithms and protocols used in low-power wireless devices, since they influence the duty-cycle of the radio.

EVA will search for energy-efficient mechanisms in low-power wireless networks. One new requirement concerns the ability to predict energy consumption with a high degree of accuracy. Scheduled communication, such as the one used in the IEEE 802.15.4 TSCH (Time Slotted CHannel Hopping) standard, and by IETF 6TiSCH, allows for a very accurate prediction of the energy consumption of a chip. Power conservation will be a key issue in EVA.

To tackle this issue and match link-layer resources to application needs, EVA's 5-year research program around Energy-Efficiency and Determinism centers around 3 studies:

- Performance Bounds of a TSCH network. We propose to study a low-power wireless TSCH network as a Networked Control System (NCS), and use results from the NCS literature. A large number of publications on NCS, although dealing with wireless systems, consider wireless links to have perfect reliability, and do not consider packet loss. Results from these papers can not therefore be applied directly to TSCH networks. Instead of following a purely mathematical approach to model the network, we propose to use a non-conventional approach and build an empirical model of a TSCH network.
- Distributed Scheduling in TSCH networks. Distributed scheduling is attractive due to its scalability and reactivity, but might result in a sub-optimal schedule. We continue this research by designing a distributed solution based on control theory, and verify how this solution can satisfy service level agreements in a dynamic environment.

3.6. Network Deployment

Since sensor networks are very often built to monitor geographical areas, sensor deployment is a key issue. The deployment of the network must ensure full/partial, permanent/intermittent coverage and connectivity. This technical issue leads to geometrical problems which are unusual in the networking domain.

We can identify two scenarios. In the first one, sensors are deployed over a given area to guarantee full coverage and connectivity, while minimizing the number of sensor nodes. In the second one, a network is re-deployed to improve its performance, possibly by increasing the number of points of interest covered, and by ensuring connectivity. EVA will investigate these two scenarios, as well as centralized and distributed approaches. The work starts with simple 2D models and will be enriched to take into account more realistic environment: obstacles, walls, 3D, fading.

3.7. Data Gathering and Dissemination

A large number of WSN applications mostly do data gathering (a.k.a "convergecast"). These applications usually require small delays for the data to reach the gateway node, requiring time consistency across gathered data. This time consistency is usually achieved by a short gathering period.

In many real WSN deployments, the channel used by the WSN usually encounters perturbations such as jamming, external interferences or noise caused by external sources (e.g. a polluting source such as a radar) or other coexisting wireless networks (e.g. WiFi, Bluetooth). Commercial sensor nodes can communicate on multiple frequencies as specified in the IEEE 802.15.4 standard. This reality has given birth to the multichannel communication paradigm in WSNs.

Multichannel WSNs significantly expand the capability of single-channel WSNs by allowing parallel transmissions, and avoiding congestion on channels or performance degradation caused by interfering devices.

In EVA, we will focus on raw data convergecast in multichannel low-power wireless networks. In this context, we are interested in centralized/distributed algorithms that jointly optimize the channel and time slot assignment used in a data gathering frame. The limits in terms of reliability, latency and bandwidth will be evaluated. Adaptivity to additional traffic demands will be improved.

3.8. Self-Learning Networks

To adapt to varying conditions in the environment and application requirements, the EVA team will investigate self-learning networks. Machine learning approaches, based on experts and forecasters, will be investigated to predict the quality of the wireless links in a WSN. This allows the routing protocol to avoid using links exhibiting poor quality and to change the route before a link failure. Additional applications include where to place the aggregation function in data gathering. In a content delivery network (CDN), it is very useful to predict the popularity, expressed by the number of solicitations per day, of a multimedia content. The most popular contents are cached near the end-users to maximize the hit ratio of end-users' requests. Thus the satisfaction degree of end-users is maximized and the network overhead is minimized.

3.9. Security Trade-off in Constrained Wireless Networks

Ensuring security is a sine qua non condition for the widespread acceptance and adoption of the IoT, in particular in industrial and military applications. While the Public-Key Infrastructure (PKI) approach is ubiquitous on the traditional Internet, constraints in terms of embedded memory, communication bandwidth and computational power make translating PKI to constrained networks non-trivial.

In the IETF 6TiSCH working group, and through the work on Malisa Vucinic as part of the H2020 ARMOUR project, we have started to work on a "Minimal Security" solution at the IETF. This solution is based on pre-shared keying material, and offers mutual authentication between each node in the network and central security authority, replay protection and key rotation.

4. Application Domains

4.1. Industrial Process Automation

Wireless networks have become ubiquitous and are an integral part of our daily lives. These networks are present in many application domains; the most important are detailed in this section.

Networks in industrial process automation typically perform **monitoring and control** tasks. Wired industrial communication networks, such as HART [1], have been around for decades and, being wired, are highly reliable. Network administrators tempted to "go wireless" expect the same reliability. Reliable process automation networks – especially when used for control – often impose stringent latency requirements. Deterministic wireless networks can be used in critical systems such as control loops, however, the unreliable nature of the wireless medium, coupled with their large scale and "ad-hoc" nature raise some of the most important challenges for low-power wireless research over the next 5-10 years.

Through the involvement of team members in standardization activities, the protocols and techniques will be proposed for the standardization process with a view to becoming the *de-facto* standard for wireless industrial process automation. Besides producing top level research publications and standardization activities, EVA intends this activity to foster further collaborations with industrial partners.

4.2. Environmental Monitoring

Today, outdoor WSNs are used to monitor vast rural or semi-rural areas and may be used to detect fires. Another example is detecting fires in outdoor fuel depots, where the delivery of alarm messages to a monitoring station in an upper-bounded time is of prime importance. Other applications consist in monitoring the snow melting process in mountains, tracking the quality of water in cities, registering the height of water in pipes to foresee flooding, etc. These applications lead to a vast number of technical issues: deployment strategies to ensure suitable coverage and good network connectivity, energy efficiency, reliability and latency, etc.

We work on such applications in an associate team "REALMS" comprising members from EVA, the university of Berkeley and the university of Michigan.

4.3. The Internet of Things

The general agreement is that the Internet of Things (IoT) is composed of small, often battery-powered objects which measure and interact with the physical world, and encompasses smart home applications, wearables, smart city and smart plant applications.

It is absolutely essential to (1) clearly understand the limits and capabilities of the IoT, and (2) develop technologies which enable user expectation to be met.

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[1]Highway Addressable Remote Transducer

The EVA team is dedicated to understanding and contributing to the IoT. In particular, the team will maintain a good understanding of the different technologies at play (Bluetooth, IEEE 802.15.4, WiFi, cellular), and their trade-offs. Through scientific publications and other contributions, EVA will help establishing which technology best fits which application.

4.4. Military, Energy and Aerospace

Through the HIPERCOM project, EVA has developed cutting-edge expertise in using wireless networks for military, energy and aerospace applications. Wireless networks are a key enabling technology in the application domains, as they allow physical processes to be instrumented (e.g. the structural health of an airplane) at a granularity not achievable by its wired counterpart. Using wireless technology in these domains does however raise many technical challenges, including end-to-end latency, energy-efficiency, reliability and Quality of Service (QoS). Mobility is often an additional constraint in energy and military applications. Achieving scalability is of paramount importance for tactical military networks, and, albeit to a lesser degree, for power plants. EVA will work in this domain.

Smart cities share the constraint of mobility (both pedestrian and vehicular) with tactical military networks. Vehicular Ad-hoc NETworks (VANETs) will play an important role in the development of smarter cities.

The coexistence of different networks operating in the same radio spectrum can cause interference that should be avoided. Cognitive radio provides secondary users with the frequency channels that are temporarily unused (or unassigned) by primary users. Such opportunistic behavior can also be applied to urban wireless sensor networks. Smart cities raise the problem of transmitting, gathering, processing and storing big data. Another issue is to provide the right information at the place where it is most needed.

4.5. Emergency Applications

In an "emergency" application, heterogeneous nodes of a wireless network cooperate to recover from a disruptive event in a timely fashion, thereby possibly saving human lives. These wireless networks can be rapidly deployed and are useful to assess damage and take initial decisions. Their primary goal is to maintain connectivity with the humans or mobile robots (possibly in a hostile environment) in charge of network deployment. The deployment should ensure the coverage of particular points or areas of interest. The wireless network has to cope with pedestrian mobility and robot/vehicle mobility. The environment, initially unknown, is progressively discovered and may contain numerous obstacles that should be avoided. The nodes of the wireless network are usually battery-powered. Since they are placed by a robot or a human, their weight is very limited. The protocols supported by these nodes should be energy-efficient to maximize network lifetime. In such a challenging environment, sensor nodes should be replaced before their batteries are depleted. It is therefore important to be able to accurately determine the battery lifetime of these nodes, enabling predictive maintenance.

4.6. Types of Wireless Networks

The EVA team will distinguish between opportunistic communication (which takes advantage of a favorable state) and collaborative communication (several entities collaborate to reach a common objective). Furthermore, determinism can be required to schedule medium access and node activity, and to predict energy consumption.

In the EVA project, we will propose **self-adaptive wireless networks** whose evolution is based on:

- optimization to minimize a single or multiple objective functions under some constraints (e.g. interference, or energy consumption in the routing process).
- machine learning to be able to predict a future state based on past states (e.g. link quality in a wireless sensor network) and to identify tendencies.

The types of wireless networks encountered in the application domains can be classified in the following categories.

4.6.1. *Wireless Sensor and Mesh Networks*

Standardization activities at the IETF have defined an "upper stack" allowing low-power mesh networks to be seamlessly integrated in the Internet (6LoWPAN), form multi-hop topologies (RPL), and interact with other devices like regular web servers (CoAP).

Major research challenges in sensor networks are mostly related to (predictable) power conservation and efficient multi-hop routing. Applications such as monitoring of mobile targets, and the generalization of smart phone devices and wearables, have introduced the need for WSN communication protocols to cope with node mobility and intermittent connectivity.

Extending WSN technology to new application spaces (e.g. security, sports, hostile environments) could also assist communication by seamless exchanges of information between individuals, between individuals and machines, or between machines, leading to the Internet of Things.

4.6.2. *Deterministic Low-Power Networks*

Wired sensor networks have been used for decades to automate production processes in industrial applications, through standards such as HART. Because of the unreliable nature of the wireless medium, a wireless version of such industrial networks was long considered infeasible.

In 2012, the publication of the IEEE 802.15.4e standard triggered a revolutionary trend in low-power mesh networking: merging the performance of industrial networks, with the ease-of-integration of IP-enabled networks. This integration process is spearheaded by the IETF 6TiSCH working group, created in 2013. A 6TiSCH network implements the IEEE 802.15.4e TSCH protocol, as well as IETF standards such as 6LoWPAN, RPL and CoAP. A 6TiSCH network is synchronized, and a communication schedule orchestrates all communication in the network. Deployments of pre-6TiSCH networks have shown that they can achieve over 99.999% end-to-end reliability, and a decade of battery lifetime.

The communication schedule of a 6TiSCH network can be built and maintained using a centralized, distributed, or hybrid scheduling approach. While the mechanisms for managing that schedule are being standardized by the IETF, which scheduling approach to use, and the associated limits in terms of reliability, throughput and power consumption remains entirely open research questions. Contributing to answering these questions is an important research direction for the EVA team.

4.6.3. *MANETs and VANETs*

In contrast to routing, other domains in MANETs such as medium access, multi-carrier transmission, quality of service, and quality of experience have received less attention. The establishment of research contracts for EVA in the field of MANETs is expected to remain substantial. MANETs will remain a key application domain for EVA with users such as the military, firefighters, emergency services and NGOs.

Vehicular Ad hoc Networks (VANETs) are arguably one of the most promising applications for MANETs. These networks primarily aim at improving road safety. Radio spectrum has been ring-fenced for VANETs worldwide, especially for safety applications. International standardization bodies are working on building efficient standards to govern vehicle-to-vehicle or vehicle-to-infrastructure communication.

4.6.4. *Cellular and Device-to-Device Networks*

We propose to initially focus this activity on spectrum sensing. For efficient spectrum sensing, the first step is to discover the links (sub-carriers) on which nodes may initiate communications. In Device-to-Device (D2D) networks, one difficulty is scalability.

For link sensing, we will study and design new random access schemes for D2D networks, starting from active signaling. This will assume the availability of a control channel devoted to D2D neighbor discovery. It is therefore naturally coupled with cognitive radio algorithms (allocating such resources): coordination of link discovery through eNode-B information exchanges can yield further spectrum usage optimization.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Awards

- Finalist, best paper award at the Global IoT Summit 2018, for paper "Why Channel Hopping Makes Sense, even with IEEE 802.15.4 OFDM at 2.4 GHz".

- **Thomas Watteyne** identified as "Key Innovator" by the European Commission's Innovation Radar, category "commitment" for the innovation "Online platform of testing tools for the Internet of Things".

5.1.2. Transfer

- Creationg of the Wattson Element startup, which commercializes the Falco solution (https://wefalco.fr/).

- Publication of RFC8480

6. New Software and Platforms

6.1. OpenWSN

KEYWORDS: Internet of things - 6TiSCH - 6LoWPAN - CoAP

FUNCTIONAL DESCRIPTION: OpenWSN is an open-source implementation of a fully standards-based protocol stack for the Internet of Things. It has become the de-facto implementation of the IEEE802.15.4e TSCH standard, has a vibrant community of academic and industrial users, and is the reference implementation of the work we do in the IETF 6TiSCH standardization working group.

- Partner: University of California Berkeley

- Contact: Thomas Watteyne

- URL: http://www.openwsn.org/

6.2. 6TiSCH Simulator

High-level simulator of a 6TiSCH network

KEYWORDS: Network simulator - 6TiSCH

FUNCTIONAL DESCRIPTION: The simulator is written in Python. While it doesn't provide a cycle-accurate emulation, it does implement the functional behavior of a node running the full 6TiSCH protocol stack. This includes RPL, 6LoWPAN, CoAP and 6P. The implementation work tracks the progress of the standardization process at the IETF.

- Contact: Malisa Vucinic

6.3. Argus

KEYWORDS: Cloud - Low-Power WIreless - Sniffer

FUNCTIONAL DESCRIPTION: There are three piece to the Argus:

The Argus Probe is the program which attaches to your low-power wireless sniffer and forwards its traffic to the Argus Broker.

The Argus Broker sits somewhere in the cloud. Based on MQTT, it connect Argus Probes with Argus Clients based on a pub-sub architecture.

Several Argus Clients can the started at the same time. It is a program which subscribes to the Argus Broker and displays the frames in Wireshark.

- Contact: Rémy Leone

6.4. SolSystem

Sensor Object Library System

KEYWORDS: Low-Power WIreless - Back-End System - SmartMesh IP

FUNCTIONAL DESCRIPTION: The source code is composed of the definition of the SOL structure (https://github.com/realms-team/sol), the code that runs on the manager (https://github.com/realms-team/solmanager, written in Python) and the code that runs on the server receiving the data (https://github.com/realms-team/solserver, written in Python)

- Contact: Keoma Brun-Laguna
- URL: http://www.solsystem.io/

6.5. 6TiSCH Wireshark Dissector

KEYWORDS: 6TiSCH - Wireshark

FUNCTIONAL DESCRIPTION: Implementation on the dissectors is done through an open-source repository, stable code is regularly contributed back to the main Wireshark code base.

- Contact: Jonathan Munoz

6.6. F-Interop

Remote Conformance and Interoperability Tests for the Internet of Thing

KEYWORDS: Interoperability - Iot - Conformance testing - Standardization

- Partners: UPMC - IMEC - ETSI - EANTC - Mandat International - Digital Catapult - University of Luxembourg - Device Gateway
- Contact: Rémy Leone

6.7. Mercator

KEYWORDS: Deployment - Low-Power WIreless - Testbeds - Connectivity

FUNCTIONAL DESCRIPTION: The firmware is written as part of the OpenWSN project. Scripts and analysis tools are written in Python.

- Contact: Keoma Brun-Laguna

7. New Results

7.1. From SmartMarina to Falco

Participants: Keoma Brun-Laguna, Thomas Watteyne.

SmartMarina project (http://smartmarina.org/) was a technical project in 2017 to study the feasibility of using the wireless technology developed at Inria-EVA for marina management. In 2018, the Wattson Elements company was born, which now commercializes the Falco solution (https://wefalco.fr/).

7.2. 6TiSCH Standardization

Participants: Malisa Vucinic, Jonathan Muñoz, Tengfei Chang, Yasuyuki Tanaka, Thomas Watteyne.

Figure 1. Screenshot of the Falco promotional video, https://youtu.be/35HdoFLrCf0.

The standardization work at 6TiSCH remains a strong federator of the work done in the team. In 2018, the working group published the specification of the 6TiSCH Operation Sublayer (6top) Protocol, RFC8480. Work is also ongoing in the fragment forwarding space, where we are working on how ot efficient forward long IPv6 packets which are fragmented to fit in short IEEE 802.15.4 frames.

7.3. 6TiSCH Security

Participants: Malisa Vucinic, Thomas Watteyne.

The security work of Inria-EVA revolves around 6TiSCH networks and is a continuation of the efforts started during the H2020 ARMOUR project. The work focused on stabilizing the "Minimal Security" solution that has now passed the working group last call in the IETF and is pending finals reviews before being published as an RFC. The solution that is standardized enables secure network access and configuration of 6TiSCH devices under the assumption that they have been provisioned with a secret key. Ongoing work extends this solution to support true zero-configuration network setup, under the assumption that the devices have been provisioned with certificates at manufacturing time.

7.4. 6TiSCH Benchmarking

Participants: Malisa Vucinic, Tengfei Chang, Yasuyuki Tanaka, Thomas Watteyne.

With the pure 6TiSCH standardizes coming to an end, the focus of the group is moving towards benchmarking how well it works. This has results in the following action. Although seemingly different, they all contribute to the overall goal of better understand (the performance of) 6TiSCH.

We have built and put online the OpenTestbed, a collection of 80 OpenMote B boards deployed in 20 "pods". These allow us to test the performance of the OpenWSN firmware in a realistic setting. The testbed is depicted in Fig. 2. You can access its management interface at http://testbed.openwsn.org/.

Figure 2. The OpenTestbed deployed in Inria Paris since July 2018.

A tool complementary to the testbed is the 6TiSCH simulator (https://bitbucket.org/6tisch/simulator) which Yatsuyiki Tanaka is leading. The simulator now represents exactly the behavior of the 6TiSCH protocol stack, and has been a catalyst for benchmarking activities around 6TiSCH.

Beyond Inria, the benchmarking activity around 6TiSCH is a hot topic, with projects such as the 6TiSCH Open Data Action (SODA, http://www.soda.ucg.ac.me/), the IoT Benchmarks Initiative (https://www.iotbench.ethz.ch/), and the Computer and Networking Experimental Research using Testbeds (CNERT) workshop at INFOCOM, all of which Inria-EVA is very involved in.

7.5. IoT and Wireless Sensor Networks

More than 50 billions of devices will be connected in 2020. This huge infrastructure of devices, which is managed by highly developed technologies, is called Internet of Things (IoT). The latter provides advanced services, and brings economical and societal benefits. This is the reason why engineers and researchers of both industry and scientific communities are interested in this area. The Internet of Things enables the interconnection of smart physical and virtual objects, managed by highly developed technologies. WSN (Wireless Sensor Network), is an essential part of this paradigm. The WSN uses smart, autonomous and usually limited capacity devices in order to sense and monitor their environment.

7.5.1. Distributed Scheduling for IEEE 802.15.4e TSCH networks

Participants: Yasuyuki Tanaka, Pascale Minet, Thomas Watteyne.

Since the scheduling algorithm is not standardized for IEEE 802.15.4e TSCH networks, many scheduling algorithms have been proposed. Most of them are centralized, few are distributed. Among the distributed scheduling algorithms, many rely on assumptions that may be violated by real deployments. This violation usually leads to conflicting transmissions of application data, decreasing the reliability and increasing the latency of data delivery. Others require a processing complexity that cannot be provided by sensor nodes of limited capabilities. Still others are unable to adapt quickly to traffic or topology changes, or are valid only for small traffic loads.

In the study funded by the Inria ADT DASMU (Action de Developement Technologique Distributed Adaptive Scheduling for MUltichannel wireless sensor networks), we focus on a distributed scheduling algorithm that relies on realistic assumptions, does not require complex computation, is valid for any traffic load, is adaptive and compliant with the standardized protocols used in the 6TiSCH working group at IETF.

First results have been obtained and an intensive simulation campaign made with the 6TiSCH simulator has provided comparative performance results. Our proposal outperforms MSF, the 6TiSCH Minimal Scheduling Function, in terms of end-to-end latency and end-to-end packet delivery ratio. More evaluations are needed to improve the proposal (e.g. less packet drops during transient situations, less overhead) in terms of scheduled cells).

7.5.2. IoT and IEEE 802.15.4e TSCH networks

Participants: Pascale Minet, Ines Khoufi, Zied Soua.

In 2018, we focus on how an IEEE 802.15.4e is autonomously built and how nodes join the network.

To join the TSCH network, a device randomly selects a physical channel used by this network and listens to a beacon advertising this network. Since the physical channel on which the beacon is broadcast changes at each beacon slot due to channel hopping, the joining device will eventually hear a beacon sent by one of its neighbors. Upon receipt of a valid beacon, this device gets synchronized with the TSCH network.

In this study, we focus on the time needed by a node to detect a beacon sent by a TSCH network, as well as on the time needed to build a TSCH network. These times are important for industrial applications where new nodes are inserted progressively, or when failed nodes are replaced. Both times highly depend on the beacon advertisement policy, policy that is not specified in the standard and is under the responsibility of a layer upper than the MAC one. Since beacons are broadcast, they are lost in case of collisions: the vital information they carry is lost. The main problem is how to avoid collisions between two devices that are not neighbors.

That is why we propose the Enhanced Deterministic Beacon Advertising algorithm, called EDBA, that ensures a collision-free advertising of beacons. Since the beacon cells are fairly distributed in the slotframe, the average joining time is minimized. The behavior of a joining node has been modeled by a Markov chain from which the average joining time is computed, taking into account the reliability of wireless links. An intensive performance evaluation based on NS3 simulations allows us to validate this model and conclude on the very good performance of EDBA, even when compared with MBS, considered as the best advertising algorithm in the literature. These results have been published in the Annals of Telecommunications, [10].

7.5.3. *UAV-based Data Gathering*
Participants: Nadjib Achir (Paris 13), Tounsia Djamah, Paul Muhlethaler, Celia Tazibt (Paris 13).

The recent advances in wireless sensors and Unmanned Aerial Vehicles have created new opportunities for environmental control and low cost aerial data gathering. We propose to use an Unmanned Aerial Vehicle (UAV) for data gathering [36]. Basically, we have proposed a method for UAV path planning based on virtual forces and potential fields. In addition, and more importantly, we present a new approach to compute the attractive forces of the potential field.

We use as our starting point the idea used by Pereira of using a potential field approach. However, we extend this work by considering that each cell in the area apply an attractive force on the drone, not only the deployed sensors. We compared our results with those obtained with Pereira's method and we obtained better performance in terms of data collection time. In other words, for the same period of time our method collect more data. The second advantage of our approach is that it leads to a significant reduction in the distance that the drone must travel.

7.5.4. *Towards evaluating Named Data Networking for the IoT: A framework for OMNeT++*
Participants: Amar Abane, Samia Bouzefrane (Cnam), Paul Muhlethaler.

Named Data Networking is a promising architecture for emerging Internet applications such as the Internet of Things (IoT). Many studies have already investigated how NDN can be an alternative for IP in future IoT deployments. However, NDN-IoT propositions need accurate evaluation at network level and system level as well. We introduce an NDN framework for OMNeT++ [29]. Designed for low-end devices and gateways of the IoT, the framework is capable of simulating NDN scenarios at the boundary of the network and the system. The framework implementation is presented and used to study a typical aspect of NDN integration in IoT devices.

7.5.5. *Evaluation of LORA with stochastic geometry*
Participants: Bartek Blaszczyszyn (Dyogen), Paul Muhlethaler.

We present a simple, stochastic-geometric model of a wireless access network exploiting the LoRA (Long Range) protocol, which is a non-expensive technology allowing for long-range, single-hop connectivity for the Internet of Things. We assume a space-time Poisson model of packets transmitted by LoRA nodes to a fixed base station. Following previous studies of the impact of interference, we assume that a given packet is successfully received when no interfering packet arrives with similar power before the given packet payload phase, see [39]. This is as a consequence of LoRa using different transmission rates for different link budgets (transmissions with smaller received powers use larger spreading factors) and LoRa intra-technology interference treatment. Using our model, we study the scaling of the packet reception probabilities per link budget as a function of the spatial density of nodes and their rate of transmissions. We consider both the parameter values recommended by the LoRa provider, as well as proposing LoRa tuning to improve the equality of performance for all link budgets. We also consider spatially non-homogeneous distributions of LoRa nodes. We show also how a fair comparison to non-slotted Aloha can be made within the same framework.

7.5.6. *Position Certainty Propagation: A location service for MANETs*
Participants: Abdallah Sobehy, Paul Muhlethaler, Eric Renault (Telecom Sud-Paris).

Localization in Mobile Ad-hoc Networks (MANETs) and Wireless Sensor Networks (WSNs) is an issue of great interest, especially in applications such as the IoT and VANETs. We propose a solution that overcomes two limiting characteristics of these types of networks. The first is the high cost of nodes with a location sensor (such as GPS) which we will refer to as anchor nodes. The second is the low computational capability of nodes in the network. The proposed algorithm [28] addresses two issues; self-localization where each non-anchor node should discover its own position, and global localization where a node establishes knowledge of the position of all the nodes in the network. We address the problem as a graph where vertices are nodes in the network and edges indicate connectivity between nodes. The weights of edges represent the Euclidean distance between the nodes. Given a graph with at least three anchor nodes and knowing the maximum communication range for each node, we are able to localize nodes using fairly simple computations in a moderately dense graph.

7.6. Industry 4.0 and Low-Power Wireless Meshed Networks

7.6.1. *Deterministic Networking for the Industrial Internet of Things (IIoT)*

Participants: Keoma Brun-Laguna, Thomas Watteyne, Pascale Minet.

The Internet of Things (IoT) connects tiny electronic devices able to measure a physical value (temperature, humidity, etc.) and/or to actuate on the physical world (pump, valve, etc). Due to their cost and ease of deployment, battery-powered wireless IoT networks are rapidly being adopted.

The promise of wireless communication is to offer wire-like connectivity. Major improvements have been made in that sense, but many challenges remain as industrial application have strong operational requirements. This section of the IoT application is called Industrial IoT (IIoT).

The main IIoT requirement is reliability. Every bit of information that is transmitted in the network must not be lost. Current off-the-shelf solutions offer over 99.999% reliability.

Then come latency and energy-efficiency requirements. As devices are battery-powered, they need to consume as little as possible to be able to operate during years. The next step for the IoT is to target time-critical applications.

Industrial IoT technologies are now adopted by companies over the world, and are now a proven solution. Yet, challenges remain and some of the limits of the technologies are still not fully understood. In his PhD Thesis, Keoma Brun-Laguna addresses TSCH-based Wireless Sensor Networks and studies their latency and lifetime limits under real-world conditions.

We gathered 3M network statistics 32M sensor measurements on 11 datasets with a total of 170,037 mote hours in real-world and testbeds deployments. We assembled what we believed to be the largest dataset available to the networking community.

Based on those datasets and on insights we learned from deploying networks in real-world conditions, we study the limits and trade-offs of TSCH-based Wireless Sensor Networks. We provide methods and tools to estimate the network performances of such networks in various scenarios. We highlight the trade-off between short latency and long network lifetime. We believe we assembled the right tools for protocol designer to build deterministic networking to the Industrial IoT.

7.6.2. *Industry 4.0 and IEEE 802.15.4e TSCH networks*

Participants: Pascale Minet, Ines Khoufi, Zied Soua.

By the year 2020, it is expected that the number of connected objects will exceed several billions devices. These objects will be present in everyday life for a smarter home and city as well as in future smart factories that will revolutionize the industry organization. This is actually the expected fourth industrial revolution, more known as Industry 4.0. In which, the Internet of Things (IoT) is considered as a key enabler for this major transformation. IoT will allow more intelligent monitoring and self-organizing capabilities than traditional factories. As a consequence, the production process will be more efficient and flexible with products of higher quality.

To produce better quality products and improve monitoring in Industry 4.0, strong requirements in terms of latency, robustness and power autonomy have to be met by the networks supporting the Industry 4.0 applications. The wireless TSCH (Time Slotted Channel Hopping) network specified in the e amendment of the IEEE 802.15.4 standard has many appealing properties. Its schedule of multichannel slotted data transmissions ensures the absence of collisions. Because there is no retransmission due to collisions, communication is faster. Since the devices save energy each time they do not take part in a transmission, the power autonomy of nodes is prolonged. Furthermore, channel hopping enables to mitigate multipath fading and interferences.

To increase the flexibility and the self-organizing capacities required by Industry 4.0, the networks have to be able to adapt to changes. These changes may concern the application itself, the network topology by adding or removing devices, the traffic generated by increasing or decreasing the device sampling frequency, for instance. That is why the flexibility of the schedule ruling all network communications is needed.

In 2018, we show how a TSCH network can adapt to such changes. More precisely, we propose a solution ranging from network construction to data gathering. We show how a TSCH network is autonomously built, supports data gathering and is able to adapt to changes in network topology, traffic and application requirements.

The solution proposed preserves the merits of TSCH network, that can be listed hereafter. The time-slotted multichannel medium access enables parallel transmissions on several channels, leading to shorter latency and higher throughputs. In addition, channel hopping mitigates interference and multipath effects. Furthermore, since transmissions are scheduled, a conflict-free schedule is computed by the network coordinator (i.e. the CPAN). Hence, no collision occurs during data gathering. The absence of collision leads to a higher throughput, because there is no retransmission due to collisions. It also preserves nodes power autonomy.

This simple solution is based on the coexistence of several periodic slotframes. We distinguish three slotframes, which are the Beacon Slotframe, the Data Slotframe and the Shared Slotframe. The network schedule corresponds to the superposition of the three schedules given by each slotframe, where the slotframe with the highest priority wins.

This solution ensures a collision-free dissemination over the whole network. Beacons are broadcast in sequence by increasing depth of devices. This broadcast is also used to disseminate Data Schedules (new schedule or update).

In addition, this solution is adaptive. Topology, traffic or application changes are notified to the CPAN. Depending on the changes notified, the CPAN updates the current schedule or recomputes a new one. Shared slots are used to cope with unexpected events.

We compute the theoretical bounds with regard to key performance indicators and compare them with the values obtained by NS3 simulation. Simulation results confirm the theoretical upper bounds computed for network construction and data gathering. Hence, TSCH networks are able to adapt to traffic or topology changes in a reasonable time which is a strong requirement of Industry 4.0 applications. These results have been presented at the PEMWN 2018 conference in [26]. In some further work, we will study how to improve this delay to support the most demanding applications.

7.7. Machine Learning for an efficient and dynamic management of data centers

7.7.1. Data Analysis in Data Centers

Participants: Eric Renault (Telecom Sud-Paris), Selma Boumerdassi (Cnam), Pascale Minet, Ines Khoufi.

In High Performance Computing (HPC), it is assumed that all machines are homogeneous in terms of CPU and memory capacities, and that the tasks making up the jobs have similar resource requests. It has been shown that this homogeneity relating both to machine capacity and workload, although generally valid for HPC, does no longer apply to data centers. This explains why the publication of data gathered in an operational Google data center over 29 days has aroused great interest among researchers.

It is crucial to have real traces of a Google data center publicly available that are representative of the functioning of real data centers. Our goal is to analyze the data collected and to draw useful conclusions about machines, jobs and tasks as well as resource usage. Our main results have been published in [25], [24] and can be summarized as follows:

- Although 92% of machines have a CPU capacity of 0.5, there are 10 machine configurations in the data center, each configuration is characterized by a pair $(CPU\ capacity, memory\ capacity)$. The most frequent configuration is supported by only 53% of machines.

- Over the 29 days, all the machines in the data center that were removed, were restarted later after an off-period. 50% of these periods have a duration less than or equal to 1000 seconds (i.e. 16.66 minutes), suggesting a maintenance operation.

- The distribution of jobs per category reveals only one job, representing 0.002%, for the Infrastructure, 0.13% of jobs for Monitoring, 9.91% of jobs for Production, 56.30% of jobs for Other, and 33.63% of jobs for Free. 92.05% of jobs have a single task. 95.75% have fewer than 10 tasks. But 12 jobs have 5000 tasks and 114 jobs have around 1000 tasks.

- With regard to resource requests, 0.11% of jobs have a memory request and a CPU request higher than or equal to 10%.

- 94.25% of jobs wait less than 10 seconds before being scheduled. However, some of them wait for more than 1000 seconds. Such large values could be explained by the existence of placement constraints for the jobs, making them harder to place and schedule. 49% of jobs have an execution time less than 100 seconds.

Such results are needed to validate or invalidate some simplifying assumptions that are usually made when reasoning about models, and make the models more accurate for jobs and tasks as well as for available machines. Having validated these models on real data centers, they can then be used for extensive evaluation of placement and scheduling algorithms and more generally for resource allocation (i.e. CPU and memory). These algorithms can then be applied in real data centers.

Another possible use of this data set is to consider it as a learning set in order to predict some feature of the data center, such as the workload of hosts or the next arrival of jobs.

7.7.2. *Machine Learning for an Energy-Efficient Management of Data Centers*

Participants: Ruben Milocco (University Of Camahue, Argentina), Pascale Minet, Eric Renault (Telecom Sud-Paris), Selma Boumerdassi (Cnam).

To limit global warming, all industrial sectors must make effort to reduce their carbon footprint. Information and Communication Technologies (ICTs) alone generate 2% of global CO2 emissions every year. Due to the rapid growth in Internet services, data centers have the largest carbon footprint of all ICTs. According to ARCEP (the French telecommunications regulator), Internet data traffic multiplied by 4.5 between 2011 and 2016. In order to support such a growth and maintain this traffic, data centers' energy consumption needs to be optimized. The problem of managing Data Centers (DC) and clouds optimally, in the sense that the demand is met with a minimal energy cost, remains a major issue. In this research, we evaluate the maximum energy saving that can be obtained in DCs by means of a proactive management of resources. The proposed management is based on models that predict resource requests.

Diverse approaches to obtain predictive models of DCs have been studied recently. Among the most popular methods with the comparatively lowest prediction errors are the predictive models of the ARMAX family. Hence, we study the predictive model given by the ARMAX family. We compare its performance with that of the Last Value (LV) model which predicts that the next value will be equal to the current one. To the best of our knowledge, there are no studies relating to the performance bounds that can be achieved using these models. In this research, we study the limits of the improvement in terms of energy cost that can be obtained using proactive strategies for DC management based on predictive models.

Using the Google dataset collected over a period of 29 days and made publicly available, we evaluate the largest benefit that can be obtained with those two predictors.

7.8. Protocols and Models for Wireless Networks - Application to VANETs

7.8.1. *Predicting Vehicles Positions using Roadside Units: a Machine-Learning Approach*
Participants: Samia Bouzefrane (Cnam), Soumya Banerjee (Birla Institute Of Technology, Mesra), Paul Mühlethaler, Mamoudou Sangare.

We study positioning systems using Vehicular Ad Hoc Networks (VANETs) to predict the position of vehicles [35]. We use the reception power of the packets received by the Road Side Units (RSUs) and sent by the vehicles on the roads. In fact, the reception power is strongly influenced by the distance between a vehicle and a RSU. To predict the position of vehicles in this context, we adopt the machine learning methodology. As a pre-requisite, the vehicles know their positions and the vehicles send their positions in the packets. The positioning system can thus perform a training sequence and build a model. The system is then able to handle a prediction request. In this request, a vehicle without external positioning will request its position from the neighboring RSUs. The RSUs which receive this request message from the vehicle will know the power at which the message was received and will study the positioning request using the training set. In this study, we use and compare three widely recognized techniques : K Nearest Neighbors (KNN), Support Vector Machine (SVM) and Random Forest. We study these techniques in various configurations and discuss their respective advantages and drawbacks. Our results show that these three techniques provide very good results in terms of position predictions when the error on the transmission power is small.

7.8.2. *Predicting transmission success with Machine-Learning and Support Vector Machine in VANETs*
Participants: Samia Bouzefrane (Cnam), Soumya Banerjee (Birla Institute Of Technology, Mesra), Paul Mühlethaler, Mamoudou Sangare.

We study the use of the Support Vector Machine technique to estimate the probability of the reception of a given transmission in a Vehicular Ad hoc NETwork (VANET). The transmission takes place between a vehicle and a RoadSide Unit (RSU) at a given distance and with a given transmission rate. The RSU computes the statistics of the receptions and is able to compute the percentage of successful transmissions versus the distance between the vehicle and the RSU and the transmission rate. Starting from this statistic, a Support Vector Machine (SVM) scheme can produce a model. Then, given a transmission rate and a distance between the vehicle and the RSU, the SVM technique can estimate the probability of a succcessful reception. This probability can be used to build an adaptive technique which optimizes the expected throughput between the vehicle and the RSU. Instead of using transmission values of a real experiment, we use the results of an analytical model of CSMA that is customized for 1D VANETs. The model we adopt to perform this task uses a Matern selection process to mimic the transmission in a CSMA IEEE 802.11p VANET. With this model we obtain a closed formula for the probability of successful transmissions. Thus with these results we can train an SVM model and predict other values for other couples : distance, transmission rate. The numerical results we obtain show that SVM seems very suitable to predict the reception probability in a VANET.

7.8.3. *TDMA scheduling strategies for vehicular ad hoc networks: from a distributed to a centralized approach*
Participants: Mohammed Hadded, Anis Laouiti (Telecom Sud-Paris, Paul Mühlethaler.

We focus on vehicular safety applications based on the Dedicated Short Range Communication (DSRC) standard. We propose a new mechanism to alleviate channel congestion by reducing the beacons load while maintaining an accurate awareness level. Our scheme is based on the collective perception concept which consists in sharing perceived status information collected by vehicles equipped with different types of sensors (radars, lidars, cameras, etc.). To achieve our goal, we propose two main schemes [30]. The first one consists in implementing the collective perception capability on vehicles and adding a new category of status messages to share locally collected sensor data in order to reduce channels load and enhance vehicles' awareness. The second scheme concerns the accuracy level of the received information from the collective perception enabled vehicles by fixing a prior error threshold on the position. The method proposed is validated by simulations and

the results obtained are compared to those of an application based on the traditional beaconing scheme of the IEEE802.11p standard. The simulations show that the proposed scheme is able to significantly reduce the load on the control channel incurred by the beacons and the packet error ratio for different network densities and built-in sensors characteristics.

7.8.4. A Collaborative Environment Perception Approach for Vehicular Ad hoc Networks

Participants: Sadia Ingrachen, Nadjib Achir (Paris 13), Paul Mühlethaler, Tounsia Djamah (Paris 13), Amine Berqia (Paris 13).

We focus on vehicular safety applications based on the Dedicated Short Range Communication (DSRC) standard. We propose a new mechanism to alleviate channel congestion by reducing the beacons load while maintaining an accurate awareness level. Our scheme is based on the collective perception concept which consists in sharing perceived status information collected by vehicles equipped with different types of sensors (radars, lidars, cameras, etc.). To achieve our goal, we propose two main schemes [31]. The first one consists in implementing the collective perception capability on vehicles and adding a new category of status messages to share locally collected sensor data in order to reduce channels load and enhance vehicles' awareness. The second scheme concerns the accuracy level of the received information from the collective perception enabled vehicles by fixing a prior error threshold on the position. The method proposed is validated by simulations and the results obtained are compared to those of an application based on the traditional beaconing scheme of the IEEE802.11p standard. The simulations show that the proposed scheme is able to significantly reduce the load on the control channel incurred by the beacons and the packet error ratio for different network densities and built-in sensors characteristics.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

Participants: Pascale Minet, Ines Khoufi, Zied Soua.

In the framework of the CNES Launchers Research and Technology program, Inria and CNEs co-funded a study dealing with wireless sensor networks in a spatial environment. More precisely, this study deals with the improvement and performance evaluation of a solution of wireless sensor networksbased on the IEEE 802.15.4e standard of TSCH (Time Slotted Channel Hopping), operating in a spatial environment.

In space launch vehicles, a NASA study shows that the mass per channel of 0.45 kg for a wiring approach can be reduced to 0.09 kg for a wireless approach.8 A question arises: which wireless technology is able to meet the requirements of space launch vehicles in terms of latency, throughput and robustness. The IEEE 802.15.4e amendment has been designed to meet such requirements. More specifically, the Time Slotted Channel Hopping (TSCH) mode of the IEEE 802.15.4e standard that has been designed for industrial automation, process control and equipment monitoring, appears very promising for space launch vehicles. More precisely, the study for CNES deals with:

- Building an IEEE 802.15.4e TSCH network: see [11] the Acta Astronautica 2018 publication.
- Scheduling transmissions in an IEEE 802.15.4e TSCH network.
- Adapting the schedule to traffic or topology changes.

This study ended in July 2018 with very satisfying results.

8.2. Bilateral Grants with Industry

Participants: Thomas Watteyne, Felipe Moran.

Felipe Moran was awarded a 6-month EDF fellowship to conduct a 6-month internship around low-power wireless networking in extrement industrial environments. Details are confidential.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. ANR

- The GeoBot FUI project (https://geobot.fr/) is one of the most innovative, challenging and fun projects around wireless localization in the world today. It applies true innovation to a real-world problem, with a clear target application (and customer) in mind. The GeoBot partners are building a small robot (think of a matchbox-sized RC car) that will be inserted into a gas pipe, and move around it to map the location of the different underground pipes. Such mapping is necessary to prevent gas-related accidents, for example during construction. At the end of the project, this solution will be commercialized and used to map the network of gas pipe in France, before being used in worldwide. Each partner is in charge of a different aspect of the problem: robotics, analysis of the inertial data, visualization, etc. Inria is in charge of the wireless part. We will be equipping the robot with a wireless chip(set) in order to (1) communicate with the robot as it moves about in the pipes while standing on the surface, and (2) discover the relative location of the robot w.r.t. a person on the surface. Inria is evaluating different wireless technologies, benchmarking around ranging accuracy and capabilities to communicate. We start from off-the-shelf kits from different vendors and build a custom board, benchmark it, and integrate it with the other partners of the project.

9.1.2. Other collaborations

- EVA has a collaboration with Orange Labs. **Thomas Watteyne** supervises the PhD of Mina Rady, which happens under a CIFRE agreement with Orange Labs.

- EVA has a collaboration with Vedecom. **Paul Muhlethaler** supervises Fouzi Boukhalfa's PhD funded by Vedecom. This PhD aims at studying low latency and high reliability vehicle-to-vehicle communication to improve roads safety.

- EVA has an ongoing collaboration with SODEAL company, which exploits the Cap d'Agde marina, as part of the SmartMarina project.

9.2. European Initiatives

9.2.1. FP7 & H2020 Projects

The H2020 following projects are ongoing:
- H2020 SPARTA, Jan 2019 – December 2020.
- H2020 F-Interop, http://f-interop.eu/, Nov 2015 – Oct 2018.
- H2020 ARMOUR, https://www.armour-project.eu/, Feb 2016 – Jan 2018.

9.2.2. Collaborations with Major European Organizations

Inria-EVA has collaboration in 2018 with ETSI (the European Telecommunications Standards Institute) to organize the F-Interop 6TiSCH 2 Interop Event on 2-4 February 2018 in Paris.

9.3. International Initiatives

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

9.3.1.1. REALMS

- Title: Real-Time Real-World Monitoring Systems
- International Partner (Institution - Laboratory - Researcher):
  - University of California Berkeley (United States) - Civil and Environmental Engineering - Steven Glaser

- University of Michigan (United States) - Civil and Environmental Engineering - Branko Kerkez
- Start year: 2015
- See also: http://glaser.berkeley.edu et http://www-personal.umich.edu/~bkerkez/
- The Internet of Things revolution prompted the development of new products and standards; The IEEE 802.15.4e (2012) standard introduced the Time Synchronized Channel Hoping (TSCH) which can provide end-to-end reliability of 99.999 % and an energy autonomy of many years. This exceptional performance prompted the IETF to create the 6TISCH working group to standardize the integration of TSCH networks in the Internet. While the first experimental data have highlighted the great robustness of these networks, there is no data of a real network, accessible in real time, on a large scale and over a long period. Such data is needed to better model network performance and produce better products and standards. Teams of Professors Glaser and Kerkez are successfully deploying such networks to study mountain hydrology, monitor water quality and manage rainwater in urban environments. A model is missing to assist in the deployment and operation of these networks, as well as to monitor an operational network.

9.3.1.2. DIVERSITY

- Title: Measuring and Exploiting Diversity in Low-Power Wireless Networks
- International Partner (Institution - Laboratory - Researcher):
    - University of Southern California (United States) - Autonomous Networks Research Group (ANRG) - Bhaskar Krishnamachari
- Start year: 2016
- The goal of the DIVERSITY associate team is to develop the networking technology for tomorrow's Smart Factory. The two teams comes with a perfectly complementary background on standardization and experimentation (Inria-EVA) and scheduling techniques (USC-ANRG). The key topic addressed by the joint team will be networking solutions for the Industrial Internet of Things (IIoT), with a particular focus on reliability and determinism.

9.3.2. Inria International Partners

9.3.2.1. Declared Inria International Partners

Inria-EVA has a long-standing Memorandum of Understanding with the OpenMote company (http://www.openmote.com/), which runs until 2020. OpenMote emerged as a spin-off of the OpenWSN project, co-lead by **Thomas Watteyne** and Prof. Xavier Vilajosana, Professor at the Open University of Catalonia and Chief Technical Officer at OpenMote.

The collaboration has been ongoing since 2012 and at the time of writing has resulted in:

- Joint academic publications, including 7 journal articles, 1 letter, 1 book chapter, 5 conference papers, 2 tutorials and invited talks.
- Joint standardization activities, in particular in the IETF 6TiSCH working group, co-chaired by **Thomas Watteyne** and for which Prof. Xavier Vilajosana is a key contributor. This activity has resulted in the joint participation in 12 IETF face-to-face meetings, joint participation in over 100 audioconferences, co-authorship of 3 Internet-Drafts and joint organization of 2 interop events.
- Joint software development, as both institutions closely collaborate in the maintenance, development, promotion and research along the OpenWSN project, including the development of the protocol stack, the integration of novel hardware technologies, the support to the community and the participation in standardization activities and interoperability events.

This MOU is NOT a commitment of funds by any part.

9.3.2.2. Informal International Partners

The Inria-EVA collaborates extensively with Prof. Pister's group at UC Berkeley on the OpenWSN and Smart Dust projects. This activity translated into several members of the Pister team visiting Inria-EVA and vice-versa in 2018.

9.3.2.3. International Initiatives

Inria-EVA participates in the IoT Benchmarks Initiative (https://www.iotbench.ethz.ch/)

Inria-EVA will be participating in 2019 in the WirelessWine SticAm-Sud project.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

1. **Prof. Xavi Vilajosana (UOC/OpenMote)** (26-30 November 2018) working on OpenMote B bring-up with Tengfei Chang and **Thomas Watteyne**

2. **Brian Gregory Kilberg (UC Berkeley)** (11-18 September 2018) working on OpenWSN/ROS integration with **Thomas Watteyne** and Tengfei Chang

3. **Prof. Xavi Vilajosana (UOC/OpenMote)** (24-28 June 2018) working on F-Interop 6TiSCH with **Thomas Watteyne** and Tengfei Chang

4. **Pablo Modernell (UOC)** (28 May – 1 June 2018) working on F-Interop with Tengfei Chang and **Thomas Watteyne**

5. **Malisa Vucinic (U Montenegro)** (9 -16 March 2018) working on 6TiSCH Security with **Thomas Watteyne**

6. **Lance Doherty (Analog Devices)** (8-9 February 2018) working on SmartMesh IP with **Thomas Watteyne**

7. **Malisa Vucinic (U Montenegro)** (29 January-16 February 2018) working on 6TiSCH Security with **Thomas Watteyne**

9.4.2. Internships

1. **Felipe Moran**, MSc intern from ENSTA ParisTech (1 September 2017 – 31 August 2018), EDF fellow, Research Topic: mote feeding habits, SmartMesh IP, Advisor: Thomas Watteyne

2. **Fabian Rincon Vija**, MSc intern from ENSTA ParisTech (14 May – 31 August 2018), Research Topic: Extension of F-Interop to IEEE 802.15.4 sub-GHz, Advisor: Thomas Watteyne

3. **Marcelo Augusto Ferreira**, MSc intern from ENSTA ParisTech (1 May – 31 August 2018), Research Topic: Measuring Energy Consumption in F-Interop, Advisor: Thomas Watteyne

4. **Imene Ben Haddada**, Using Support Vector Machine for Positioning Services in Vehicle Ad-hoc NETworks (ENSI- Tunisia), March-July 2018.

5. **Khalifa Hadded**, Generation of positioning data in Vehicle Ad-hoc NETworks (ENSI- Tunisia), March-July 2018.

6. **Zied Soua**, Formation d'un réseau TSCH
et ordonnancement de ses communications dans le cadre de l'IoT industriel, (INSAT- Tunisia), February-July 2018.

9.4.3. Visits to International Teams

9.4.3.1. Research Stays Abroad

- **Thomas Watteyne** spent the month of August 2017 at UC Berkeley, working with Prof. Glaser on the SnowHow project, and with Prof. Pister on Smart Dust and OpenWSN.

- Tengfei Chang spent the month of July 2017 in California working with Prof. Pister working on Smart Dust UC Berkeley, and Prof. Krishnamachari working on testbed deployment at the Univesity of Southern California.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organization

10.1.1.1. General Chair, Scientific Chair

- **Thomas Watteyne** is TPC co-chair of the 6th International Workshop on Computer and Networking Experimental Research using Testbeds (CNERT), held in conjunction with IEEEINFOCOM, Paris, France, 29 April-2 May, 2019. More information at https://infocom2019.ieee-infocom.org/cnert-computer-and-networking-experimental-research-using-testbeds.

- **Paul Muhlethaler** was general co-chair with Eric Renault of the first conference of application of Machine Learning for Networks (MLN 2018 27-28 November 2018), conference hosted by Inria Paris.

- **Pascale Minet** was general co-chair with Leila Saidane from ENSI (Tunisia) of the PEMWN 2018 conference, the 7th IFIP/IEEE international conference on Performance Evaluation and Modeling of Wired and Wireless Networks, technically co-sponsored by IFIP WG6.2 and IEEE ComSoc (see https://sites.google.com/site/pemwn2018/). This conference was held in Toulouse (IUT of Blagnac), the 26th, 27th and 28th of September 2018. The organization co-chairs were Thierry Val, Adrien Van Den Bossche, and Rejane Dalce. Three tutorials were given:
    - *D2D communications in 5G networks: opportunities and challenges* by Salah Eddine Elayoubi, Centrale Supelec, Paris.
    - *Drone aided networks: from collecting data to connecting people* by Riadh Dhaou, Institut National Polytechnique de Toulouse (INPT).
    - *Continuity of the Positioning Service* by François Spies, University Bourgogne Franche-Comte.

- **Thomas Watteyne** was co-chair of the 6TiSCH 2 Plugtests, Inria, Paris,2-4 February 2018.

10.1.1.2. Member of the Organizing Committees

- **Paul Muhlethaler** organized the DGA Inria workshop on Artificial Intelligence for telecommunications and networks in May 2018.

10.1.2. Scientific Events Selection

10.1.2.1. Chair of Conference Program Committees

- **Paul Muhlethaler** was in Steering committee member of MobileHealth Workshop 2018.

- **Anis Louiti** was in Steering committee member of MobileHealth Workshop 2018.

10.1.2.2. Member of the Conference Program Committees

- **Pascale Minet**
    - CoRes 2018, 3emes Rencontres Francophones sur la Conception de Protocoles,
    - DCNET 2018, 9th International Conference on Data Communication Networking, July 2018,
    - ETFA 2018, 22th IEEE International Conference on Emerging Technologies & Factory Automation, September 2018,
    - EUSPN 2018, 9th International Conference on Emerging Ubiquitous Systems and Pervasive Networks (EUSPN), November 2018,
    - GlobeCom 2018, IEEE Global Communications Conference, December 2018.
    - MLN 2018, Machine Learning for Networking, November 2018,

– MSPN 2018, 4th International Conference on Mobile, Secure and Programmable Networking, June 2018,

– PEMWN 2018, 7th International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks, September 2018,

– PECCS 2018, 8th International conference on Pervasive and Embedded Computing and Communication Systems, July 2018,

– SITIS 2018, 14th International Conference on Signal Image Technology & Internet Based Systems, November 2018,

– VTC 2018, 87th IEEE Vehicular Technology Conference, June 2018,

– Wireless Days 2018, IFIP/IEEE Wireless Days, March 2018,

– WiSEE 2018, 6th IEEE International Conference on Wireless for Space and Extreme Environments, October 2018.

- **Paul Muhlethaler**:

  – ITST 2018 15- 17 October, Lisbon, Portugal ,

  – ISCC 2018, 25-28 June 2018, Natal Brazil,

  – Mownet 2018, International Conference on Selected Topics in Mobile & Wireless Networking, 20 -22 June 2018,

  – PEMWN 2018, 7th International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks, 26 - 28 November 2018, Toulouse,

  – Wireless Days, IFIP/IEEE Wireless Days 3 - 5 April 2018, Dubai,

  – WiOpt 2018, 7 - 11 March 2018 Shangai, China.

10.1.3. Journal

10.1.3.1. Reviewer - Reviewing Activities

- **Paul Muhlethaler**

  – Reviewer Ad Hoc Networks Journal (Elsevier),

  – Reviewer Annals of telecommunications,

  – Reviewer International Journal of Distributed Sensor Networks. Hindawi,

  – Reviewer IEEE Transactions on Information Theory,

  – Reviewer IEEE Transactions on Vehicular Technology,

  – Reviewer IEEE Transactions on Wireless Communications.

- **Pascale Minet**

  – Acta Astronautica,

  – Ad Hoc Networks,

  – Annals of Telecommunications,

  – Computer Communications,

  – Computer Networks,

  – Engineering Applications of Artificial Intelligence,

  – IEEE Access,

  – IEEE Internet of Things,

  – IEEE Transactions on Mobile Computing,

  – IEEE Transactions on Green Communications and Networking,

  – IEEE Transactions on Industrial Electronics,

  – IEEE Transactions on Industrial Informatics,

- International Journal of Communication Systems,
- International Journal of Ad Hoc and Ubiquitous Computing,
- Sensors Journal,
- Wireless Networks.

- **Thomas Watteyne**
    - MDPI Sensors, 2018.
- Nadjib Achir
    - Reviewer Sensor Networks (MDPI)
    - Reviewer Wireless Communications and Mobile Computing (Wiley)
    - Reviewer Internet of Things Journal (IEEE)
    - Reviewer Ad Hoc Networks Journal (Elsevier)
- Selma Boumerdassi
    - Reviewer Ad Hoc Networks Journal (Elsevier);
    - Reviewer The journal of Future Generation Computer Systems (Elsevier).
- Samia Bouzefrane
    - The International Journal of Computer and Telecommunications Networking (Elsevier),
    - The IEEE Transactions on Mobile Computing,
    - The Information and Software Technology Journal (Elsevier)
    - The Springer Multimedia Tools and Application Journal
    - The ACM Transaction on Internet Technology
    - The Concurrency and Computation Practice and Experience Journal
    - the Journal of Systems and Software (Elsevier)

10.1.4. Invited Talks

- **Thomas Watteyne**
    - Panelist on "New Trends for IoT and Satellite Networks", talking about "Industrial IoT, A Reality Check – Standards, Products and Research Challenges" at IoT Week 2018, Bilbao, Spain, 6 June 2018.
    - Boostez la Performance the vos Objects Connectes. Inria Tech talk, French Tech central, Station F, Paris, France. 24 October 2018.
    - Getting Your Hands Dirty with the Industrial IoT and SmartMesh IP. Summer School on Dependable IoT. TU Graz, Graz, Austria. 20 July 2018.
    - SmartMesh IP. Captronic/Arrow mesh networking day. ESSIE, Paris, France. 25 October 2018.
    - The Internet of (Important) Things. French Tech Central, Station F, Paris, France. 24 October 2018.
    - "IoT research, standardization and interop using testbeds", Fed4FIRE Engineering Conference, Brugge, Belgium, 8-9 October 2018.
    - From Research, to Product, to Standardization: A Journey into TSCH. TU Graz, Graz, Austria, 19 July 2018.
    - Reality Check on IoT Solutions producing data for people to analyze. Boston Consultancy Group semine series, Station F, Paris, France. 7 July 2018.
    - (keynote) Industrial IoT, A Reality Check : Standards, Products and Research Challenges. IIoT Workshop, Strasbourg, France, 3 July 2018.

– "IPv6 over the TSCH mode of IEEE 802.15.4e: overview of standardization, tooling, open-source initiative and commercial products", Workshop on Design, Deployment and Testing of Internet of Things Technologies (DDT-IoT), IEEE BalkanCom, Podgorica, Montenegro, 8 June 2018.

– "Industrial IoT, A Reality Check: Standards, Products and Research Challenges", IoT Week, Bilbao, Spain, 4-8 June 2018.

– A Turn-Key Solution for Real-World IoT, presented together with Keoma Brun-Laguna. LIRIMA Workshop on Smart Agriculture in Africa. 3-4 April 2018.

– Intro to Dr. Malisa Vucinic' keynote "The Devil is in the Detail: How a Real-World IoT Technology is Made – IETF 6TiSCH" at the Information Technology Conference, Montenegro, 20 February 2018.

10.1.5. *Leadership within the Scientific Community*

Thomas Watteyne co-chairs the IETF 6TiSCH standardization group.

10.1.6. *Scientific Expertise*

Thomas Watteyne regularly consults with major player in the (Industrial) IoT space.

10.1.7. *Research Administration*

- **Thomas Watteyne** is member of the Inria-Paris "Commission de Developpement Technologique", since 2018, where we ensure Inria project teams get sufficient engineering resources to change the world.

- **Paul Muhlethaler** is member of the Inria-Paris "Comite de Centre", since 2016 (suppléant of Michel Kern).

- **Thomas Watteyne** is member of the Inria-Paris "Comite de Centre", since 2016, where we work on making sure Inria-Paris will always remain one of the greatest places to work at!

10.2. Teaching - Supervision - Juries

10.2.1. *Teaching*

- Intensive 1-week course on IoT, with associated hands-on labs. ENSTA ParisTech. Graduate level. **Thomas Watteyne** and Ziran Zhang. 9-12 October 2017.

- 1/2-day crash course on the Industrial IoT. Telecom ParisTech. Graduate level. **Thomas Watteyne**. 28 September 2017..

- 6-week course on IoT, with associated hands-on labs. ENSTA ParisTech. Undergraduate level. **Thomas Watteyne**, Keoma Brun-Laguna and Dominique Barthel. Spring 2017.

10.2.2. *Supervision*

- PhD : Fouzi Boukhalfa, Low and high reliability access in Vehicular Ad-hoc NETworks. Sorbonne University. **Paul Muhlethaler**.

- PhD (ongoing) Mina Rady, Heterogeneous architectures for the IoT, Sorbonne University. **Thomas Watteyne** and **Paul Muhlethaler**, under a CIFRE agreement with Orange Labs, Meylan, France.

- PhD (viva on 18 December 2018) Keoma Brun-Laguna, Deterministic networking for the Industrial Internet of Things, Sorbonne University. **Thomas Watteyne** and **Pascale Minet**.

- PhD (in progress) Jonathan Munoz, Time slotted systems for long range communications, Sorbonne University, **Thomas Watteyne** and **Paul Muhlethaler**.

- PhD (in progress) Amar Abane, Name Data Networks in the Internet of Things, CNAM. Samia Bouzefrane and **Paul Muhlethaler**.

- PhD (in progress) Abdallah Soheby, Etude et evaluation de la dissemination des informations dans la 5G. Eric Renault and **Paul Muhlethaler**.
- PhD (in progress) Mamoudou Sangara, Utilisation de techniques de Machine Leraning dans les reseaux VANETs. Samia Bouzefrane and **Paul Muhlethaler**.
- PhD (in progress) Iman Hmedoush, Connection protocols for the 5G IoT. Cedric Adjih and **Paul Muhlethaler**.

10.2.3. Juries

- HdR:
  – Oyunchimeg Shagdar, "Optimizing wireless communications in dense mobile environments", University of Paris-Saclay, prepared at the University of Versailles-Saint Quentin, September 2018, **Pascale Minet** examiner.
  – Imen Jemili, "Optimisation des ressources dans les réseaux mobiles sans fil", University of Bordeaux, November 2018, **Pascale Minet** examiner.
  – Khaled Boussetta "Dimensionnement, adaptation et placement de fonctionnalités réseaux pour des applications sensibles aux délais", University of Paris 13, December 2018, **Paul Muhlethaler** reviewer.

- PhD:
  – Keoma Brun-Laguna, "Deterministic networking for the Industrial Internet of Things", Sorbonne University, December 2018, **Thomas Watteyne** and **Pascale Minet**, PhD advisers.
  – of Jetmir Haxhibeqiri, "Flexible and Scalable Wireless Communication Solutions for Warehouse Applications", imec – IDLab Ghent – Ghent University, Belgium, December 2018, **Thomas Watteyne** reviewer.
  – Narjes Boulila "Communication vehiculaire garantissant les contraintes temps reel pour les systèmes de prevention de collision", University de la Manouba, December 2018, **Paul Muhlethaler** reviewer.
  – Dinh Van Nguyen "Reseaux de capteurs sans-fil pour la cartographie à l'interieure et la localisation precise servant la navigation à basse vitesse dans les villes intelligentes", Mines ParisTech, December 2018, **Paul Muhlethaler** examiner.
  – Veronica Quintuna Rodriguez "Performance Analysis of Virtualized Network", University of Paris 6, October 2018, **Paul Muhlethaler** examiner.
  – Mohamed Tahar Hammi, "Sécurisation de l'Internet des Objets", Telecom ParisTech, September 2018, **Pascale Minet** examiner.
  – Lilia Lassouaoui, "Ordonnancement et routage pour l'augmentation de la duree de vie dans les reseaux de capteurs sans fil", CNAM, July 2018, **Pascale Minet** examiner.
  – Thiwiza Bellache. "Controle dynamique des communications dans une environnement V2V et V2I", University Versailles Saint Quentin February 2018. **Paul Muhlethaler** examiner.
  – Philippe Erzan "Optimisation de la topologie des reseaux sans fil", University Centrale-Supelec, January 2018, **Paul Muhlethaler** examiner.
  – Moussa Déthié Sarr, "Spécification d'un mécanisme de construction automatique de topologies et d'adressage permettant la gestion dynamique de réseaux de capteurs sans fil lineéaires", University of Clermont, January 2018, **Pascale Minet** reviewer.
  – Pengwenlong Gu, "Détection des comportements malveillants dans les réseaux véhiculaires", Telecom ParisTech, February 2018, **Pascale Minet** examiner.

10.3. Popularization

10.3.1. Interventions

- Keoma Brun-Laguna
  - "Solsystem: IoT Industriel et déploiement en milieux réels" démo at RII meeting ("Mobil-ités et environnements, 20 Novembre 2018, Station F, Paris")
- **Thomas Watteyne**
  - The Inria-Paris OpenTestbed (you might already have noticed...). Inria Seminar, Paris, 2 October 2018.
  - "Le tour du monde en 1,000 capteurs!". Inria Rocquencourt seminar series. 6 June 2018.
  - Construire son Reseau IoT en 10min. Conférence d'ouverture de la semaine des Mathé-matiques. Inria-Paris, Paris, France, 12 March 2018.

10.3.2. Dans les Medias

- **Thomas Watteyne**
  - Edge computing: on vous dit tout sur les technos qui mettent le cloud dans votre poche, 01net, 10 September 2018.
  - Qu'est-ce que l'IoT? Boston Consultancy Group podcast, 9 September 2018.
  - Retour Semaine des maths 2018 : conference de Thomas Watteyne à l'Inria, Academie de Paris, 15 March 2018.

10.3.3. Creation of media or tools for science outreach

A video concerning the research on protocols for VANETs of Mohamed Hadded has been done by Inria.

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Publications of the year

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