Activity Report 2019

Project-Team EVA

Wireless Networking for Evolving & Adaptive Applications

RESEARCH CENTER
Paris

THEME
Networks and Telecommunications

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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

Research Scientists
Pascale Minet [Inria, Researcher, HDR]
Paul Muhlethaler [Team leader, Inria, Senior Researcher, HDR]
Malisa Vucinic [Inria,Starting Research Position]
Thomas Watteyne [Inria,Senior Researcher, HDR]

Post-Doctoral Fellow
Timothy Claeys [Inria, from Dec 2019]

PhD Students
Mina Rady [CIFRE with Orange Labs, started January 2019]
Razanne Abu Aisheh [CIFRE with Nokia Bell Labs, started December 2019]
Amar Abane [CNAM, from Mar 2019 until Jul 2019]
Iman Hmedoush [Inria]
Jonathan Munoz Soto [Inria, until March 2019]
Mamoudou Sangare [Univerity Conakry, from October 2017 until december 2020]
Abdallah Sobehy [Univ Paris-Saclay]
Fouzi Boukhalfa [Vedecom from October 2018 until September 2021]

Technical staff
Jonathan Munoz Soto [From April 2019 GeoBot, Engineer]
Trifun Savic [GeoBot, Engineer, from Feb 2019]
Keoma Brun-Laguna [Inria, ATT SmartMarina, Engineer]
Tengfei Chang [Inria, ADT 6TiSCH, Engineer]
Yasuyuki Tanaka [Inria, ADT DASMU, Engineer]

Interns and Apprentices

Miguel Landry Foko Sindjoung [Inria, Intern, from Mar 2019 until Jun 2019]
Sharut Gupta [Inria, from May 2019 until Jul 2019]
Ba Hai Le [Inria, Intern, from Apr 2019 until Aug 2019]
Amy Hane [Inria,Inter, from Sep 2019 until dec 2019]
Camilo Andres Lopez Lopez [Inria, Intern, from May 2019 until Aug 2019]
Victor Kenichi Nascimento Kobayashi [Inria,Intern, from May 2019 until Aug 2019]

Visiting Scientists

Elsa Nicol [CEO & Co-Founder, Wattson Elements, Falco]
Olivier Laporte [Customer Support Europe & Co-Founder, Wattson Elements, Falco]
Martina Brachmann [RISE, Sweden, Postdoc, Nov 2019]
Ana Laura Diedrichs [UTN, Argentina, PhD student, Oct-Nov 2019]
Leila Azouz [ENSI Tunis, Professor, Oct 2019]
Randy Hare [GeoBot project, Jun-Aug 2019]
Diego Dujovne [Universidad Diego Portales, Chile, July 2019]
Branko Kerkez [U. Michigan, USA, Professor, May 2019]
Mikolaj Chwalisz [TU Berlin, PhD student, May 2019]

External Collaborators

Kris Pister [UC Berkeley, REALMS associate team]
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Nadjib Achir [Habilite]
Selma Boumerdassi [CNAM]
Samia Bouzefrane [CNAM]
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Mohamed Elhadad [Vedecom]
Oyunchimeg Shagdar [Vedecom]

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 to 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 and LAKE standardization working groups, 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. HiPERCOM2 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 studies 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 studies 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 dealing with 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 investigate self-learning networks. Machine learning approaches, based on experts and forecasters, are 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 popularity, expressed by the number of requests per day, for 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. Internet of Things Security

Existing Internet threats might steal our digital information. Tomorrow's threats could disrupt power plants, home security systems, hospitals. The Internet of Things is bridging our digital security with personal safety. Popular magazines are full of stories of hacked devices (e.g. drone attack on Philips Hue), IoT botnets (e.g. Mirai), and inherent insecurity.

Why has the IoT industry failed to adopt the available computer security techniques and best practices? Our experience from research, industry collaborations, and the standards bodies has shown that the main challenges are:

1. The circumvention of the available technical solutions due to their inefficiency.
2. The lack of a user interface for configuring the product in the field resulting in default parameters being (re)used.
3. Poorly tested software, often lacking secure software upgrade mechanisms.

Our research goal is to contribute to a more secure IoT, by proposing technical solutions to these challenges for low-end IoT devices with immediate industrial applicability and transfer potential. We complement the existing techniques with the missing pieces to move towards truly usable and secure IoT systems.

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, protocols and techniques are 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.

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[1] Highway Addressable Remote Transducer

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.

The EVA team is dedicated to understanding and contributing to the IoT. In particular, the team maintains 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 helps establish 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 remain 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

- Startup Falco wins the Innovation Competition at the Paris Nautic Show (200.000 visitors), December 2019
- Startup Falco wins the Favorite Startup Pitch battle at MassChallenge, Boston, November 2019
- Startup Falco wins the Amplify Pitch battle, October 2019
- Startup Falco awardee of the prestigous Netva “Deeptech North America” program, June 2019
- Startup Falco awardee of the prestigous WILCO/WILCOMET accelerator program
- Amar Abane and **Paul Muhlethaler** receive the best student paper award at PEMWN 2019 for the paper “Modeling and Improving Named Data Networking over IEEE 802.15.4”
- Abdallah Sobehy, under the supervision of **Paul Muhlethaler** and Eric Renault from EVA, secured the first place in the Indoors Positioning Competition held during the IEEE’s Communication Theory Workshop 2019, Selfoss, Iceland. The objective was to localize a transmitter using Channel State Information (CSI) received at a Massive MIMO antenna which is one of the main drivers of the 5G. The contesters were provided with training data to develop algorithms that predict the transmitter’s position from CSI. On the competition day, the teams were given 2000 CSI readings to predict the corresponding positions using the developed algorithms. The evaluation criterion is the Mean Square Error (MSE) of the predicted positions. The proposed method relies on CSI preprocessing and Deep Learning (Multi-Layer Perceptron Neural Network). With an MSE of 2.3 cm, the proposed solution clinched the first place among 8 teams from top universities around the world such as: University of Toronto (Canada), Ruhr University Bochum (Germany). Heriot-Watt University (England), University of Padova (Italy), IMdea networks institute (Spain), Aalborg University (Denmark), and Yuan Ze University (Taiwan).
- Abdellah Sobehy receives the “Le premier prix du jury” during the fifth edition of‘ “la journée doctorants de Samovar”

5.1.2. Transfer

- Internet Engineering Steering Group (IESG) approval of draft-ietf-6tisch-minimal-security to be published as RFC
- Malisa Vucinic named co-chair of the IETF LAKE standardization working group
- Thomas Watteyne co-chairs IETF working group 6TiSCH
- Thomas Watteyne co-chairs IETF design team of fragment forwarding
- Thomas Watteyne part of the IETF IoT directorate
- Startup Falco had a booth at the Paris Nautic Show (Dec 2019, 200.000 visitors)
- Startup Falco had a booth at the Cap d'Agde Nautic Show (Oct-Nov 2019, 50.000 visitors)
- Startup Falco selected to join the Parisian Incubator Agoranov, April 2019

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: Remy 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 Muñoz

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: Remy 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. Falco startup launched!

Participants: Elsa Nicol, Keoma Brun-Laguna, Thomas Watteyne.

The Falco startup (https://wefalco.com/) was launched on 14 January 2019. During 2019, it developed a complete technical solution (PCB, assembly, networking, back-end) and completed a large market development campaign. Falco was selected to join the Parisian Incubator Agoranov. It was then awarded the prestigous Netva "Deeptech North America" program, and won the Favorite Startup Pitch battle at MassChallenge, Boston, as well as the Amplify Pitch battle. It had a booth at the Cap d'Agde and Paris Nautic shows. On 14 December 2019, Falco wins the Innovation Competition at the Paris Nautic Show.

7.2. 6TiSCH Standardization

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

The standardization work at 6TiSCH remains a strong federator of the work done in the team. In 2019, the working group finalized the work on the draft-ietf-6tisch-minimal-security and draft-ietf-6tisch-architecture specification, which are both in the editor queue. The draft-ietf-6tisch-msf has also passed the working group last call. This standardization work has resulted in several papers on 6TiSCH, including a tutorial [9], [11], [12] fragmentation in 6TiSCH [8], implementation details [17], simulating 6TiSCH [24], experimental approaches [21], [26], localization [25], multi-PHY extensions [10]. The HDR of Thomas Watteyne [2] reports on the work on 6TiSCH over the past years. Some work has started on implementing 6TiSCH on single-chip micro-motes [19], [23], [7], [18].

7.3. 6TiSCH Security

Participants: Malisa Vucinic, Thomas Watteyne.

The security work of Inria-EVA is a continuation of the efforts started during the H2020 ARMOUR project. The work focused on stabilizing the “Minimal Security” solution that has now been approved to be published as an RFC [13]. 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 resulted in the following action. Although seemingly different, they all contribute to the overall goal of better understanding (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. You can access its management interface at http://testbed.openwsn.org/.

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 [26] (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. LAKE Standardization

Participants: Malisa Vucinic, Timothy Claeys, Thomas Watteyne.

In October 2019, a new working group was formed in the IETF with the goal of standardizing a lightweight authenticated key exchange protocol for IoT use cases. The group is co-chaired by Malisa Vucinic of Inria-EVA. Through our work in 6TiSCH and the requirements for the follow up work of the “Minimal Security Framework for 6TiSCH”, we directly contributed to the creation of this working group whose expected output is the key exchange protocol for the IoT. The document we lead in the LAKE working group [37] compiles the requirements for a lightweight authenticated key exchange protocol for OSCORE. OSCORE (RFC8613) is a lightweight communication security protocol providing end-to-end security on application layer for constrained IoT settings. It is expected to be deployed with standards and frameworks using CoAP such as 6TiSCH, LPWAN, OMA Specworks LwM2M, Fairhair Alliance and Open Connectivity Foundation.

7.6. IoT and Low-Power Wireless Meshed Networks

More than 50 billion devices will be connected in 2020. This huge infrastructure of devices, which is managed by highly developed technologies, is called the Internet of Things (IoT). The IoT provides advanced services, and brings economic and societal benefits. This is the reason why engineers and researchers in 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. Low-Power Wireless Meshed Network is an essential part of this paradigm. It uses smart, autonomous and usually limited capacity devices in order to sense and monitor their environment.

7.6.1. Centralized or Distributed Scheduling for IEEE 802.15.4e TSCH networks

Participants: Yasuyuki Tanaka, Pascale Minet, Thomas Watteyne, Malisa Vucinic, Tengfei Chang, Keoma Brun-Laguna.

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 mitigates multipath fading and interferences.

All communication in a TSCH network is orchestrated by the communication schedule it is using. The scheduling algorithm used hence drives the latency and capacity of the network, and the power consumption of the nodes. To increase the flexibility and the self-organizing capacities required by IoT, 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 flexibility of the schedule ruling all network communications is needed. We have designed a number of scheduling algorithms for TSCH networks, answering different needs. For instance, the centralized Load-based scheduler that assigns cells per flow, starting with the flow originating from the most loaded node has proved optimal for many configurations. Simulations with the 6TiSCH simulator showed that it gets latencies close to the optimal. They also highlighted that end-to-end latencies are positively impacted by message prioritization (i.e. each node transmits the oldest message first) at high loads, and negatively impacted by unreliable links, as presented at GlobeCom 2019 [30].

Among the distributed scheduling algorithms proposed in the literature, 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. We have designed MSF and YSF, two distributed scheduling algorithms that are adaptive and compliant with the standardized protocols used in the 6TiSCH working group at IETF. The Minimal Scheduling Function (MSF) is a distributed scheduling algorithm in which neighbor nodes locally negotiate adding and removing cells. MSF was evaluated by simulation and experimentation, before becoming the default scheduling algorithm of the IETF 6TiSCH working group, and now an official standard. We also designed LLSF, a scheduling algorithm focused on low latency communication. We proposed a full-featured 6TiSCH scheduling function called YSF, that autonomously takes into account all the aspects of network dynamics, including the network formation phase and parent switches. YSF aims at minimizing latency and maximizing reliability for data gathering applications. Simulation results obtained with the 6TiSCH simulator show that YSF yields lower end-to-end latency and higher end-to-end reliability than MSF, regardless of the network topology. Unlike other top-down scheduling functions, YSF does not rely on any assumption regarding network topology or traffic load, and is therefore more robust in real network deployments. 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.

Furthermore we published additional research on computing the upper bounds on the end-to-end latency, finding the best trade-off between latency and network lifetime.

7.6.2. Modeling and Improving Named Data Networking over IEEE 802.15.4

Participants: Amar Abane, Samia Bouzefrane (Cnam), Paul Muhlethaler.

Enabling Named Data Networking (NDN) in real world Internet of Things (IoT) deployments becomes essential to benefit from Information Centric Networking (ICN) features in current IoT systems. One objective of the model is to show that caching can attenuate the number of transmissions generated by broadcast to achieve a reasonable overhead while keeping the data dissemination power of NDN. To design realistic NDN-based communication solutions for IoT, revisiting mainstream technologies such as low-power wireless standards may be the key. We explore the NDN forwarding over IEEE 802.15.4 by modeling a broadcast-based forwarding [27]. Based on the observations, we adapt the Carrier-Sense Multiple Access (CSMA) algorithm of 802.15.4 to improve NDN wireless forwarding while reducing broadcast effects in terms of packet redundancy, round-trip time and energy consumption. As future work, we aim to explore more complex CSMA adaptations for lightweight forwarding to make the most of NDN and design a general-purpose Named-Data CSMA.

7.6.3. Evaluation of LORA with stochastic geometry

Participants: Bartek Blaszczyszyn (Dyogene), 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 [16]. 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 how a fair comparison to non-slotted Aloha can be made within the same framework.

7.6.4. Position Certainty Propagation: A location service for MANETs

Participants: Abdallah Sobehy, Paul Muhlethaler, Eric Renault (Telecom Sud-Paris).

A location method based on triangulation (via Channel State Information (CSI) based localization method is proposed [6]. A known method of triangulation is adopted to deduce the location of a node from 3 reference nodes (anchor nodes). We propose an optimized energy-aware and low computational solution, requiring 3-GPS equipped nodes (anchor nodes) in the network. Moreover, the computations are lightweight and can be implemented distributively among nodes. Knowing the maximum range of communication for all nodes and distances between 1-hop neighbors, each node localizes itself and shares its location with the network in an efficient manner. We simulate our proposed algorithm on a NS-3 simulator, and compare our solution with state-of-the-art methods. Our method is capable of localizing more nodes i.e. $\simeq 90\%$ of nodes in a network with an average degree $\simeq 10$.

7.7. Industry 4.0 and Low-Power Wireless Meshed Networks

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 direction, but many challenges remain as industrial applications have strong operational requirements. This section of the IoT application is called Industrial IoT (IIoT).

By the year 2020, it is expected that the number of connected objects will exceed several billion 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, better known as Industry 4.0. In which, the Internet of Things (IoT) is considered as a key enabler for this major transformation. The 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.

7.7.1. *Reliability for the Industrial Internet of Things (IIoT) and Industry 4.0*

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

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.

To provide the end-to-end reliability targeted by industrial applications, we investigate an approach based on message retransmissions (on the same path). We propose two methods to compute the maximum number of transmissions per message and per link required to achieve the targeted end-to-end reliability. The MFair method is very easy to compute and provides the same reliability over each link composing the path, by means of different maximum numbers of transmissions, whereas the MOpt method minimizes the total number of transmissions necessary for a message to reach the sink. MOpt provides a better reliability and a longer lifetime than MFair, which provides a shorter average end-to-end latency. This study [5] was published in the Sensors journal in 2019.

7.8. Machine Learning applied to Networking

7.8.1. *Machine Learning for energy-efficient and QoS-aware Data Centers*

Participants: Ruben Milocco (Comahue University, Argentina, Invited Professor), 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.

We determine whether resource allocation in DCs can satisfy the three following requirements: 1) meet user requirements (e.g. short response times), 2) keep the data center efficient, and 3) reduce the carbon footprint.

An efficient way to reduce the energy consumption in a DC is to turn off servers that are not used for a minimum duration. The high dynamicity of the jobs submitted to the DC requires periodically adjusting the number of active servers to meet job requests. This is called Dynamic Capacity Provisioning. This provisioning can be based on prediction. In such a case, a proactive management of the DC is performed. The goal of this study is to provide a methodology to evaluate the energy cost reduction brought by proactive management, while keeping a high level of user satisfaction.

The state-of-the art shows that appropriate proactive management improves the cost, either by improving QoS or saving energy. As a consequence, there is great interest in studying different proactive strategies based on predictions of either the energy or the resources needed to serve CPU and memory requests. The cost depends on 1) the proactive strategy used, 2) the workload requested by jobs and 3) the prediction used. The problem complexity explains why, despite its importance, the maximum cost savings have not been evaluated in theoretical studies.

We propose a method to compute the upper bound of the relative cost savings obtained by proactive management compared to a purely reactive management based on the Last Value. With this method, it becomes possible to quantitatively compare the efficiency of two predictors.

We also show how to apply this method to a real DC and how to select the value of the DC parameters to get the maximum cost savings. Two types of predictors are studied: linear predictors, represented by the ARMA model, and nonlinear predictors obtained by maximizing the conditional probability of the next sample, given the past. They are both applied to the publicly available Google dataset collected over a period of 29 days. We evaluate the largest benefit that can be obtained with those two predictors. Some of these results have been presented at HPCS 2019 [20].

7.8.2. *Machine Learning applied to IoT networks*

Participants: Miguel Landry Foko Sindjoung (Phd Student, Dschang University, Cameroon, Inria Internship), Pascale Minet.

Knowledge of link quality in IoT networks allows a more accurate selection of wireless links to build the routes used for data gathering. The number of re-transmissions is decreased, leading to shorter end-to-end latency, better end-to-end reliability and a longer network lifetime.

We propose to predict link quality by means of machine learning techniques applied on two metrics: the Received Signal Strength Indicator (RSSI) and the Packet Delivery Ratio (PDR). These two metrics were selected because RSSI is a hardware metric that is easily obtained and PDR takes into account packets that are not successfully received, unlike RSSI.

The data set used in this study was collected from a TSCH network deployed in the Grenoble testbed consisting of 50 nodes operating on 16 channels. Data collected by Mercator include 108659 measurements of PDR and average RSSI. We train the model over the training set and predict the link quality on the channel considered for the samples in the validation set. By comparing the predicted values with the real values, the confusion matrix is computed by evaluating the number of true-positive, true-negative, false-positive and false-negative for the link and channel considered.

Whatever the link quality estimator used, RSSI, PDR or both, the Random Forest (RF) classifier model outperforms the other models studied: Linear Regression, Linear Support Vector Machine, Support Vector Machine.

Since using Bad links that have been predicted Good strongly penalizes network performance in terms of end-to-end latency, end-to-end reliability and network lifetime, the joint use of PDR and RSSI improves the accuracy of link quality prediction. Hence, we recommend using the Random Forest classifier applied on both PDR and RSSI metrics. This work has been presented at the PEMWN 2019 conference [33].

7.9. Machine Learnig applied to Smart Farming

Participants: Jamal Ammouri (Internship Cnam), Malika Boudiaf (Ummto, Tizi-Ouzou, Algeria), Samia Bouzefrane (Cnam), Pascale Minet, Meziane Yacoub (Cnam).

Intelligent Farming System (IFS) is made possible by the use of 4 elements: sensors and actuators, the Internet of Things (IoT), edge/cloud processing, and machine learning.

Soil degradation and a hot climate explain the poor yield of olive groves in North Algeria. Edaphic, climatic and geographical data were collected from 10 olive groves over several years and analyzed by means of Self-Organizing Maps (SOMs). SOM is a non-supervised neural network that projects high-dimensional data onto a low-dimension discrete space, called a topological map, such that close data are mapped onto nearby locations on the map. In the paper [28] presented at the PEMWN 2019 conference, we have shown how to use self-organizing maps to determine olive grove clusters with similar features, characterize each cluster and show the temporal evolution of each olive grove. With the SOM, it becomes possible to alert the farmer when some specific action needs to be done in the case of hydric stress, NPK stress, pest/disease attack. As a result, the nutritional quality of the oil produced is improved. SOM can be integrated in the Intelligent Farming System (IFS) to boost conservation agriculture.

This work requires a strong collaboration with agronomists. Malika Boudiaf (Laboratoire Ressources Naturelles, UMMTO, Tizi-Ouzou, Algeria) provided the data set and gave us many explanations about soil conservation. Meziane Yacoub (Cnam) is an expert in SOMs. Jamal Ammouri (Cnam) was co-advised by Samia Bouzefrane, Pascale Minet and Meziane Yacoub.

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

7.10.1. Connection-less IoT - Protocol and models

Participants: Iman Hemdoush, Cédric Adjih, Paul Mühlethaler.

The goal is to construct some next-generation access protocols, for the IoT (or alternately for vehicular networks). One starting point are methods from the family of Non-Orthogonal Multiple Access (NOMA), where multiple transmissions can "collide" but can still be recovered - with sophisticated multiple access protocols (MAC) that take the physical layer/channel into account. One such example is the family of the Coded Slotted Aloha methods.Another direction is represented by some vehicular communications where vehicles communicate directly with each other without necessarily going through the infrastructure. This is also true more generally in any wireless network where the control is relaxed (such as in unlicensed IoT networks like LoRa). One observation is that in such distributed scenarios, explicit or implicit forms of signaling (with sensing, messaging, etc.), can be used for designing sophisticated protocols - including using machine learning techniques.

During this study, some of the following tools should be used: protocol/algorithm design (ensuring properties by construction), simulations (ns-2, ns-3, matlab, ...) on detailed or simplified network models, mathematical modeling (stochastic geometry, etc...) ; machine-learning techniques or modeling as code-on-graphs.

The first result we have obtained concerns Irregular Repetition Slotted Aloha (IRSA) which is a modern method of random access for packet networks that is based on repeating transmitted packets, and on successive interference cancellation at the receiver. In classical idealized settings of slotted random access protocols (where slotted ALOHA achieves $1/e$), it has been shown that IRSA could asymptotically achieve the maximal throughput of 1 packet per slot. Additionally, IRSA had previously been studied for many different variants and settings, including the case where the receiver is equipped with “multiple-packet reception” (MPR) capability. We extensively revisit the case of IRSA with MPR. We present a method to compute optimal IRSA degree distributions with a given maximum degree n. A tighter bound for the load threshold (G/K) was proven, showing that plain K-IRSA cannot reach the asymptotic known bound $G/K = 1$ for $K > 1$, and we prove a new, lower bound for its performance. Numerical results illustrate that optimal degree distributions can approach this bound. Second, we analyze the error floor behavior of K-IRSA and provide an insightful approximation of the packet loss rate at low loads, and show its excellent performance. Third, we show how to formulate the search for the appropriate parameters of IRSA as an optimization problem, and how to solve it efficiently. By doing that for a comprehensive set of parameters, and by providing this work with simulations, we give numerical results that shed light on the performance of IRSA with MPR. A final open question is: what is the impact of introducing more structure in the slot selection (like Spatially Coupled Coded Slotted Aloha) and how best to do so?

7.10.2. Indoor positionning using Channel State Information (CSI) from a MIMO antenna

Participants: Abdallah Sobehy, Paul Muhlethaler, Eric Renault (Telecom Sud-Paris).

The channel status information is used for locating a node by applying machine learning [35] techniques. We propose a novel lightweight deep learning solution to the indoor positioning problem based on noise and dimensionality reduction of MIMO Channel State Information (CSI): real and imaginary parts of the signal received. Based on preliminary data analysis, the magnitude of the CSI is selected as the input feature for a Multilayer Perceptron (MLP) neural network. Polynomial regression is then applied to batches of data points to filter noise and reduce input dimensionality by a factor of 14. The MLP’s hyper-parameters are empirically tuned to achieve the highest accuracy. The method is applied to a CSI dataset estimated at an 8 x 2 MIMO antenna that is published by the organizers of the Communication Theory Workshop Indoor

Positioning Competition. The proposed solution is compared with a state-of-the-art method presented by the authors who designed the MIMO antenna that is used to generate the data-set. Our method yields a mean error which is 8 times less than that of its counterpart. We conclude that the arithmetic mean and standard deviation misrepresent the results since the errors follow a log- normal distribution. The mean of the log error distribution of our method translates to a mean error as low as 1.5 cm. We have shown that, using a K-nearest neighbor learning method an even better, indoor positioning is achieved. The input feature is the magnitude component of CSI which is pre-processed to reduce noise and allow for a quicker search. The Euclidean distance between CSI is the criterion chosen for measuring the closeness between samples. The proposed method is compared with three other methods, all based on deep learning approaches and tested with the same data-set. The K-nearest neighbor method presented in this paper achieves a Mean Square Error (MSE) of 2.4 cm, which outperforms its counterparts.

7.10.3. 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. 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. We have already used and compared three widely recognized techniques : K Nearest Neighbors (KNN), Support Vector Machine (SVM) and Random Forest. We have studied these techniques in various configurations and discuss their respective advantages and drawbacks. We revisit the positioning problem VANETs but we also consider Neural Networks (NN) to predict the position [22]. The neural scheme we have tested in this paper consists of one hidden layer with three neurons. To boost this technique we use an ensemble neural network with 50 elements built with a bagging algorithm. The numerical experiments presented in this contribution confirm that a precise prediction can only be obtained when there is a main direct path of propagation. The prediction is altered when the training is incomplete or less precise but the precision remains acceptable. In contrast, with Rayleigh fading, the accuracy obtained is much less striking. We observe that the Neural Network is nearly always the best approach. With a direct path the ranking is: Neural Network, Random Forest, KNN and SVM except in the case when we have no measurement in [30m; 105m] where the ranking is Neural Network, Random Forest, SVM and KNN. When there is no direct path, the ranking is SVM, NN, RF and KNN but the difference in performance between SVM and NN is small.

7.10.4. Combining random access TDMA scheduling strategies for vehicular ad hoc networks

Participants: Fouzi Boukhalfa, Mohamed Hadded (Vedecom), Paul Mühlethaler, Oyunchimeg Shagdar (Vedecom).

This work is based on Fouzi Boukhalfa's PhD which started in October 2018, [29],[15]. The idea is to combine TDMA protocols with random access techniques to benefit from the advantages of both techniques. Fouzi Boukhalfa proposes to combine the DTMAC protocol introduced by Mohamed Hadded with a generalization of CSMA. This generalized CSMA uses active signaling; the idea is to send signaling bursts in order to select a unique transmitter. The protocol that Fouzi Boukhalfa obtains reduces the access and merging collisions of DTMAC but can also propose access with low latency for emergency traffic. The idea is that vehicles access their slots reserved with DTMAC but the transmission slots encompass a special section at the beginning with active signaling. The transmission of the signaling burst, during a mini-slot, is organized according to a random binary key. A '1' in the key means that a signaling burst will be transmitted, while a '0' means that the vehicle senses the channel on this mini-slot to potentially find the transmission of a signaling burst by another vehicle. Fouzi Boukhalfa shows that if we use a random key to transmit the signaling burst it very significantly decreases the collision rate (both merging and access collisions) and that emergency traffic can have a very small access delay. Fouzi Boukhalfa builds an analytical model which thoroughly confirms the simulation result. This model can encompass detection error in the selection process of the signaling bursts. It is shown that with a reasonable error rate the performance is only marginaly affected.

7.10.5. Forecasting traffic accidents in VANETs

Participants: Samia Bouzefrane (Cnam), Soumya Banerjee (Birla Institute Of Technology, Mesra), Paul Mühlethaler, Mamoudou Sangare.

Road traffic accidents have become a major cause of death. With increasing urbanization and populations, the volume of vehicles has increased exponentially. As a result, traffic accident forecasting and the identification of the accident prone areas can help reduce the risk of traffic accidents and improve the overall life expectancy.

Conventional traffic forecasting techniques use either a Gaussian Mixture Model (GMM) or a Support Vector Classifier (SVC) to model accident features. A GMM on the one hand requires large amount of data and is computationally inexpensive, SVC on the other hand performs well with less data but is computationally expensive. We present a prediction model that combines the two approaches for the purpose of forecasting traffic accidents. A hybrid approach is proposed, which incorporates the advantages of both the generative (GMM) and the discriminant model (SVC). Raw feature samples are divided into three categories: those representing accidents with no injuries, accidents with non incapacitating injuries and those with incapacitating injuries. The output or the accident severity class was divided into three major categories namely: no injury in the accident, non-incapacitating injury in the accident and an incapacitating injury in the accident. A hybrid classifier is proposed which combines the descriptive strength of the baseline Gaussian mixture model (GMM) with the high performance classification capabilities of the support vector classifier (SVC). A new approach is introduced using the mean vectors obtained from the GMM model as input to the SVC. The model was supported with data pre-processing and re-sampling to convert the data points into suitable form and avoid any kind of biasing in the results. Feature importance ranking was also performed to choose relevant attributes with respect to accident severity. This hybrid model successfully takes advantage of both models and obtained a better accuracy than the baseline GMM model. The radial basis kernel outperforms the linear kernel by achieving an accuracy of 85.53%. Data analytics performed including the area under the receiver operating characteristics curve (AUC-ROC) and area under the precision/recall curve(AUC-PR) indicate the successful application of this model in traffic accident forecasting. Experimental results show that the proposed model can significantly improve the performance of accident prediction. Improvements of up to 24% are reported in the accuracy as compared to the baseline statistical model (GMM). The data about circumstances of personal injury in road accidents, the types of vehicles involved and the consequential casualties were obtained from data.govt.uk.

Although a significant improvement in accuracy has been observed, this study has several limitations. The first concerns the dataset used. This research is based on a road traffic accident dataset from the year of 2017 which contains very few data samples for the no injury and non-incapacitating injury types of accident. The data was unbalanced not just with respect to the output class but also with respect to the sub features of various attributes. Moreover, aggregating the accident severity into just three categories limits the scope of the study and the results obtained. The greater the number of severity classes, the less is the amount of extra training data required to feed in the SVC to avoid overfitting. Thus, datasets with sufficient records corresponding to each class are desirable and must be used for further study.

The second limitation concerns the dependence of the SVC model on parameters and attribute selection. In this study, the performance of SVC relies heavily on the feature selection results and the mean vectors obtained from the GMM. In order to improve the accuracy of the support vector classifier, other approaches like particle swarm optimization (PSO), ant colony optimization, genetic algorithms etc. could be used for effective parameter selection. In addition to this, more kernels like the polynomial kernel and the sigmoid kernel could be tested to improve future model performances.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Grants with Industry

Participants: Razanne Abu Aisheh, Mina Rady, Thomas Watteyne.

Razanne Abu Aisheh is doing her PhD under a CIFRE agreement between Inria and Nokia Bell Labs. Mina Rady is doing his PhD under a CIFRE agreement between Inria and Orange Labs.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. Inria Project Labs, Exploratory Research Actions and Technological Development Actions

- IPL SPARTA
- ATT SmartMarina, 2019. Help transfer the technology of the SmartMarina project to startup Falco. Keoma Brun-Laguna is lead.
- ADT 6TiSCH, 2018-2020. Benchmark the performance of 6TiSCH under realistic scenarios, through experimentaion using the OpenTestbed. Tengfei Chang is lead.
- ADT DASMU (Distributed Adaptive Scheduling for MUltichannel Wireless Sensor Networks), 2018-2019. DASMU focuses on a distributed scheduling algorithm which 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, called YSF, outperforms MSF, the 6TiSCH Minimal Scheduling Function, in terms of end-to-end latency and end-to-end packet delivery ratio. Thanks to this ADT, Yasuyuki Tanaka has joined the EVA team for two years.

9.1.2. 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.

9.1.3. 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 runs the Cap d'Agde marina, as part of Falco startup.
- EVA has an ongoing collaboration with SELOR company, which runs the Lorient marinas, as part of the Falco startup.

9.2. European Initiatives

9.2.1. FP7 & H2020 Projects

The H2020 following project is ongoing:

- H2020 SPARTA, Jan 2019 – December 2020.

9.2.2. Collaborations in European Programs, Except FP7 & H2020

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. The 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.

9.3.2. 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-led 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 party.

9.3.2.2. Informal International Partners

The Inria-EVA team 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.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

1. **Martina Brachmann (RISE, Sweden)** (November 2019) working on TSCH on the RISE: Current Research and Future Directions in Networked Embedded Systems with Thomas Watteyne, Malisa Vucinic, Tengfei Chang
2. **Ana Laura Diedrichs (UTN, Argentina)** (Oct-Nov 2019) working on WirelessWine with Thomas Watteyne, Keoma Brun-Laguna
3. **Prof Leila Seidane Azouz** 1-30 October 2019 working with **Pascale Minet** and **Paul Muhlethaler** on wireless networks.
4. **Prof Ruben Milocco** visited EVA from 1-30 October 2019 working with **Pascale Minet** on evaluation of data center performance and **Paul Muhlethaler** on wireless network relaying.
5. **Prof. Diego Dujovne (UDP, Chile)** (July 2019) working on WirelessWine with Thomas Watteyne
6. **Prof. Branko Kerkez (U. Michigan)** (May 2019) working on REALMS associate team with Thomas Watteyne
7. **Mikolaj Chwalisz (TU Berlin)** (May 2019) working on Towards efficient coexistence of IEEE 802.15.4e TSCH and IEEE 802.11 Collaboration with Tengfei Chang, Thomas Watteyne

9.4.1.1. Internships

1. Amy Hane, Intern, from Sep 2019 until Dec 2019
2. Camilo Andres Lopez Lopez, Intern, from May 2019 until Aug 2019
3. Ba Hai Le, Intern, Apr-Aug 2019
4. Victor Kenichi Nascimento Kobayashi,Intern, from May 2019 until Aug 2019
5. Sharut Gupta, Intern, from May 2019 until July 2019
6. Miguel Landry Foko Sindjoung, Intern, from Mar 2019 until Jun 2019.

9.4.1.2. Research Stays Abroad

- **Thomas Watteyne** spent the month of August 2019 at UC Berkeley, working with Prof. Glaser on the SnowHow project, and with Prof. Pister on Smart Dust and OpenWSN.
- Tengfei Chang spent June 2019 in California working with Prof. Pister working on Smart Dust UC Berkeley.

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 IEEE INFOCOM, 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 second conference of application of Machine Learning for Networks (MLN 2019 3-5 December 2019), a conference hosted by Inria Paris. Two tutorials and two keynotes were given:
  - *Cloud Solution Architect (Artificial Intelligence and Machine Learning)* by Franck Gaillard (Microsoft, France) [tutorial 1].
  - *Towards intelligent mobile networks* by Marie Line Alberi Morel (NOKIA Bell Lab, France) and Kamal Singh (Télécom Saint-Etienne / University Jean Monnet, France) [tutorial 2].
  - *From Learning to Reasoning : A topos perspective* by Jean-Claude Belfiore (Huawei, France) [keynote 1].
  - *Paradigm shifts in communication networks: cloud-native, automation and AI/ML* by Alberto Conte (NOKIA Bell Labs, France) [keynote 2]

  Thirty two technical presentations have been given during the three days of the MLN 2019 conference.
- **Pascale Minet** was general co-chair with Leila Saidane from ENSI (Tunisia) of the PEMWN 2019 conference, the 8th IFIP/IEEE international conference on Performance Evaluation and Modeling of Wired and Wireless Networks, technically co-sponsored by IFIP WG6.2 and IEEE ComSoc. This conference was held in Paris (Inria Research Center), the 26th, 27th and 28th of November 2018. Three tutorials were given:
  - *Information Centric Networks: Toward an Internet of Named Objects* by Andrea Araldo, Telecom Sud-Paris, France.
  - *Shannon versus Turing, the limit of Artificial Intelligence* by Philippe Jacquet, Inria, Paris-Saclay, France.
  - *5G: Key technologies, standard and evolutions* by Marceau Coupechoux, Telecom ParisTech, France.

  Fourteen technical presentations have been given during the three days of the PEMWN 2019 conference.

10.1.1.2. Member of the Organizing Committees

- **Paul Muhlethaler** organized the DGA Inria workshop on the topic ”Au dela des communications quantiques, les réseaux quantique” in May 2019.

10.1.2. Scientific Events Selection

10.1.2.1. Chair of Conference Program Committees

- **Paul Muhlethaler** was a Steering committee member of IWVSC 2019.
- **Pascale Minet** was chair of the Technical Program Committee of PEMWN 2019, 8th International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks, November 2019.

10.1.2.2. Member of Conference Program Committees

- **Pascale Minet**
  - CoRes 2019, 4emes Rencontres Francophones sur la Conception de Protocoles, l’Evaluation de Performance et l’Expérimentation des Réseaux de Communication, May 2019.
  - EUSPN 2019, 10th International Conference on Emerging Ubiquitous Systems and Pervasive Networks (EUSPN), November 2019.,
  - GlobeCom 2019, IEEE Global Communications Conference, December 2019.
  - IWVSC 2019, 3rd International Workshop on Vehicular Adhoc Networks for Smart Cities, November 2019,

  - MLN 2019, Machine Learning for Networking, December 2019,
  - MSPN 2019, 5th International Conference on Mobile, Secure and Programmable Networking, June 2019,
  - PECCS 2019, 9th International conference on Pervasive and Embedded Computing and Communication Systems, September 2019,
  - VTC 2019, 88th IEEE Vehicular Technology Conference, September 2019,
  - Wireless Days 2019, IFIP/IEEE Wireless Days, April 2019,
  - WiSEE 2019, 7th IEEE International Conference on Wireless for Space and Extreme Environments, October 2019.
- **Paul Muhlethaler**:
  - ISCC 2019, 30 June -28 July 2019, Barcelona Spain,
  - MLN 2019, Machine Learning for Networking, December 2019, Paris.
  - PEMWN 2019, 8th International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks, 26 - 28 November 2019, Paris,
  - Wireless Days, IFIP/IEEE Wireless Days 24 - 26 April 2019, Manchester

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,
  - Reviewer MDPI Sensors
- **Pascale Minet**
  - Acta Astronautica,
  - Ad Hoc Networks,
  - Annals of Telecommunications,
  - Computer Communications,
  - Computer Networks,
  - Engineering Applications of Artificial Intelligence,
  - Future Internet,
  - IEEE Access,
  - IEEE Internet of Things,
  - IEEE Transactions on Mobile Computing,
  - IEEE Transactions on Industrial Informatics,
  - International Journal of Advanced Intelligence Paradigms,
  - International Journal of Communication Systems,
  - Sensors Journal,
  - Wireless Networks.
- 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**
  - SmartMesh IP. Captronic/Arrow mesh networking day. Montpellier, France, 13 June 2019.
  - OpenTestbed; Poor Man's IoT Testbed. TILECS Workshop. Grenoble, France. 4 July 2019.
  - SmartMesh IP. Captronic/Arrow mesh networking day. Toulouse, France, 18 April 2019.
- **Pascale Minet**
  - "Estimation and Prediction of Link Quality in Low-Power Wireless Mesh Networks" at the Machine Learning for Networking (MLN) conference, December 2019, Paris.

10.1.5. Leadership within the Scientific Community

Thomas Watteyne co-chairs the IETF 6TiSCH standardization group. **Malisa Vucinic** co-chairs the IETF LAKE standardization group.

10.1.6. Scientific Expertise

- **Thomas Watteyne** regularly consults with major player in the (Industrial) IoT space.
- **Pascale Minet** was also reviewer of a proposal submitted to the Call for Generic Projects issued by the ANR.

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 (alternate 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!
- **Pascale Minet** is member of the Inria-Paris "Commission d'Emplois Scientifiques" (Delegations, Postdocs, and PhD scholarship) since 2018.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

- **Thomas Watteyne** teaches 6-week course on IoT, with associated hands-on labs. Undergraduate level. ENSTA ParisTech. Together with Tarak Arbi and Dominique Barthel. Spring 2019.
- **Thomas Watteyne**teaches 1/2-day crash course on the Industrial IoT, Telecom ParisTech. Graduate level. 27 September 2019.
- **Thomas Watteyne**teaches 1-day hands-on course on IIoT, and support of subsequent projects, MsC level, University College London, 6 February 2019.

10.2.2. Supervision

- PhD : Fouzi Boukhalfa, Low and high reliability access in Vehicular Ad-hoc NETworks. Sorbonne University. **Paul Muhlethaler**.
- PhD (ongoing) Razanne Abu Aisheh, Robotics, Sorbonne University. **Thomas Watteyne**,
- 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 (defended) 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 Learning 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:
  - Hichem Sedjelmaci “Attacks Detection and Prediction Frameworks Based on AI Techniques for Wireless and Mobile Networks” Univeristy de Burgundy, October 2019 **Paul Muhlethaler** reviewer.
  - Katia Jaffres-Runser, "Modélisations et Optimisation Multicritere de Réseaux", Institut National Polytechnique de Toulouse, July 2019, **Pascale Minet** reviewer.
- PhD:
  - Vasileios Kotsiou, “Reliable Communications for the Industrial Internet of Things”, University of Strasbourg, France, **Thomas Watteyne** examiner.
  - Meriem Smache, “Deterministic Network Security for the Industrial Internet of Things (IIoT)”, CEA and École des Mines de Saint-Étienne, France, **Thomas Watteyne** examiner.
  - Esteban Municio, “Towards Scalable and End-to-End Programmable Industrial Internet of Things”, University of Antwerpen , Belgium, **Thomas Watteyne** examiner.
  - Amel Arfaoui. “Game based for security of Intenet of things” Univeristy de Burgundy, 15 October 2019 **Paul Muhlethaler** examiner
  - Amar Abane. “Une Architecture Réaliste pour l’IOT” Cnam and University of Tizi Ouzou 2 December 2019 **Paul Muhlethaler** examiner

  - Karen Boulos, "BBU-RRH Association Optimization in Cloud-Radio Access Networks", University of Paris-Saclay, July 2019, **Pascale Minet** reviewer.
  - Jinpeng Wang, "Impact of Mobility and Deployment in Confined Spaces on Low Power and Lossy Network", University of Clermont-Auvergne, July 2019, **Pascale Minet** examiner.
  - Yoann Desmouceaux, "Network Layer Protocols for Data Center Scalability", University of Paris-Saclay, April 2019, **Pascale Minet** examiner.

10.3. Popularization

10.3.1. Dans les Medias

- **Thomas Watteyne**
  - Falco : Des capteurs pour connecter ports et plaisanciers. BoatIndustry, 15 November 2019
  - Agde : le port connecté, une réalité. Midi Libre, 31 October 2019.
  - Gestion portuaire : les ports de Lorient et Cap d'Agde entrent dans l'ère du port connecté, Actu Maritime, 1 August 2019.
  - Port connecté : un nouveau cap franchi grâce à Falco (an interview of our startup's CEO Elsa Nicol), inria.fr, 18 February 2019.

10.3.2. Creation of media or tools for science outreach

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

11. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] J. M. MUNOZ SOTO. *km-scale Industrial Networking*, UPMC - Sorbonne University, March 2019, https://hal.inria.fr/tel-02285706

[2] T. WATTEYNE. *The Internet of (Important) Things*, Sorbonne Universite, May 2019, Habilitation à diriger des recherches, https://hal.inria.fr/tel-02135069

Articles in International Peer-Reviewed Journals

[3] A. ABANE, M. DAOUI, S. BOUZEFRANE, P. MUHLETHALER. *A lightweight forwarding strategy for Named Data Networking in low-end IoT*, in "Journal of Network and Computer Applications", 2019, vol. 148, 102445 p. [*DOI :* 10.1016/J.JNCA.2019.102445], https://hal.archives-ouvertes.fr/hal-02334088

[4] A. ABANE, M. DAOUI, S. BOUZEFRANE, P. MUHLETHALER. *NDN-over-ZigBee: A ZigBee support for Named Data Networking*, in "Future Generation Computer Systems", April 2019, vol. 93, pp. 792-798 [*DOI :* 10.1016/J.FUTURE.2017.09.053], https://hal.archives-ouvertes.fr/hal-02411296

[5] P. MINET, Y. TANAKA. *Optimal Number of Message Transmissions for Probabilistic Guarantee in the IoT*, in "Sensors", September 2019, https://hal.archives-ouvertes.fr/hal-02433637

[6] A. Sobehy, E. Renault, P. Muhlethaler. *Position certainty propagation: a localization service for Ad-Hoc Networks*, in "Computers", January 2019, vol. 8, n^{o} 1, Article 6 [*DOI :* 10.3390/COMPUTERS8010006], https://hal.archives-ouvertes.fr/hal-02178389

[7] I. Suciu, F. Maksimovic, B. Wheeler, D. Burnett, O. Khan, T. Watteyne, X. Vilajosana, K. Pister. *Dynamic Channel Calibration on a Crystal-Free Mote-on-a-Chip*, in "IEEE Access", August 2019 [*DOI :* 10.1109/ACCESS.2019.2937689], https://hal.inria.fr/hal-02420914

[8] Y. Tanaka, P. Minet, T. Watteyne. *6LoWPAN Fragment Forwarding*, in "IEEE Communications Standards Magazine", July 2019, vol. 3, n^{o} 1, pp. 35-39, https://hal.inria.fr/hal-02061838

[9] P. Thubert, X. V. Guillen, T. Watteyne. *6TiSCH, enabling IPv6 over 802.15.4 TSCH*, in "IEEE Communications Standards Magazine", March 2019, https://hal.inria.fr/hal-02420677

[10] P. Tuset-Peiró, F. Vazquez-Gallego, J. M. Munoz Soto, T. Watteyne, J. Alonso-Zarate, X. Vilajosana. *Experimental Interference Robustness Evaluation of IEEE 802.15.4-2015 OQPSK-DSSS and SUN-OFDM Physical Layers for Industrial Communications*, in "Sensors", September 2019, https://hal.inria.fr/hal-02420946

[11] X. Vilajosana, T. Watteyne, T. Chang, M. Vučinić, S. Duquennoy, P. Thubert. *IETF 6TiSCH: A Tutorial*, in "Communications Surveys and Tutorials, IEEE Communications Society", September 2019, forthcoming, https://hal.inria.fr/hal-02420974

[12] X. Vilajosana, T. Watteyne, M. Vučinić, T. Chang, K. Pister. *6TiSCH: Industrial Performance for IPv6 Internet of Things Networks*, in "Proceedings of the IEEE", June 2019, vol. 107, n^{o} 6, pp. 1153 - 1165 [*DOI :* 10.1109/JPROC.2019.2906404], https://hal.inria.fr/hal-02266569

[13] M. Vučinić, J. Simon, K. Pister, M. Richardson. *Constrained Join Protocol (CoJP) for 6TiSCH*, in "Internet Engineering Task Force", 2019, forthcoming, https://hal.inria.fr/hal-02407587

[14] Z. Zhang, S. D. Glaser, T. Watteyne, S. Malek. *Long-term Monitoring of the Sierra Nevada Snowpack Using Wireless Sensor Networks*, in "IEEE internet of things journal", June 2020, https://hal.inria.fr/hal-01388391

International Conferences with Proceedings

[15] F. Boukhalfa, M. Hadded, P. Muhlethaler, O. Shagdar. *An Analytical Model for Performance Analysis of an Active Signaling-based TDMA MAC Protocol for Vehicular Networks*, in "VTC-FALL 2019 - IEEE Vehicular Technology Conference", Honolulu, Hawaii, United States, September 2019, https://hal.archives-ouvertes.fr/hal-02178355

[16] B. Błaszczyszyn, P. Muhlethaler. *Analyzing LoRa long-range, low-power, wide-area networks using stochastic geometry*, in "VALUETOOLS 2019 - 12th EAI International Conference on Performance Evaluation Methodologies and Tools", Palma de Mallorca, Spain, Proc. ACM VALUETOOLS, ACM, 2019, https://arxiv.org/abs/1811.01886 - 8 pages [*DOI :* 10.1145/3306309.3306327], https://hal.inria.fr/hal-01958939

[17] T. Chang, T. Watteyne, X. Vilajosana. *Competition: OpenWSN, a Development Environment for 6TiSCH*, in "International Conference on Embedded Wireless Systems and Networks (EWSN)", Beijing, China, February 2019, https://hal.inria.fr/hal-01968644

[18] T. CHANG, T. WATTEYNE, B. WHEELER, F. MAKSIMOVIC, O. KHAN, S. MESRI, L. LEE, K. PISTER, I. SUCIU, X. VILAJOSANA. *Demo: 6TiSCH on SCμM, Running a Synchronized Protocol Stack without Crystals*, in "EWSN 2020 - ACM International Conference on Embedded Wireless Systems and Networks", Lyon, France, February 2020, https://hal.inria.fr/hal-02436262

[19] F. MAKSIMOVIC, B. WHEELER, D. BURNETT, O. KHAN, S. MESRI, I. SUCIU, L. LEE, A. MORENO, A. SUNDARARAJAN, B. ZHOU, R. ZOLL, A. NG, T. CHANG, X. VILAJOSANA, T. WATTEYNE, A. NIKNEJAD, K. PISTER. *A Crystal-Free Single-Chip Micro Mote with Integrated 802.15.4 Compatible Transceiver, sub-mW BLE Compatible Beacon Transmitter, and Cortex M0*, in "2019 VLSI - IEEE Symposium on VLSI Technology & Circuits", Kyoto, Japan, June 2019 [*DOI :* 10.23919/VLSIC.2019.8777971], https://hal.inria.fr/hal-02420868

[20] R. MILOCCO, P. MINET, E. RENAULT, S. BOUMERDASSI. *Cost reduction bounds of proactive management based on request prediction*, in "HPCS 2019: 17th International Conference on High Performance Computing & Simulation", Dublin, Ireland, 2019 International Conference on High Performance Computing & Simulation (HPCS), IEEE Computer Society, 2019, pp. 1-10, https://hal.archives-ouvertes.fr/hal-02432652

[21] J. M. MUNOZ SOTO, F. RINCON, T. CHANG, X. VILAJOSANA, B. VERMEULEN, T. WALCARIUS, W. VAN DE MEERSSCHE, T. WATTEYNE. *OpenTestBed: Poor Man's IoT Testbed*, in "IEEE INFOCOM - CNERT : Workshop on Computer and Networking Experimental Research using Testbeds", Paris, France, April 2019, https://hal.inria.fr/hal-02266558

[22] M. SANGARE, D.-V. N. NGUYEN, S. BANERJEE, P. MUHLETHALER, S. BOUZEFRANE. *Comparing different Machine-Learning techniques to predict Vehicles' Positions using the received Signal Strength of periodic messages*, in "WMNC 2019. 12th IFIP Wireless and Mobile Networking Conference", Paris, France, September 2019, https://hal.archives-ouvertes.fr/hal-02178360

[23] I. SUCIU, F. MAKSIMOVIC, D. BURNETT, O. KHAN, B. WHEELER, A. SUNDARARAJAN, T. WATTEYNE, X. VILAJOSANA, K. PISTER. *Experimental Clock Calibration on a Crystal-Free Mote-on-a-Chip*, in "IEEE INFOCOM - CNERT 2019 : International Workshop on Computer and Networking Experimental Research using Testbeds", Paris, France, April 2019, https://hal.inria.fr/hal-02266563

[24] Y. TANAKA, K. BRUN-LAGUNA, T. WATTEYNE. *Demo: Simulating a 6TiSCH Network using Connectivity Traces from Testbeds*, in "CNERT - IEEE INFOCOM Workshop on Computer and Networking Experimental Research using Testbeds", Paris, France, April 2019, https://hal.inria.fr/hal-02266552

[25] Y. TANAKA, H. LE, V. KOBAYASHI, C. LOPEZ, T. WATTEYNE, M. RADY. *Demo: Blink - Room-Level Localization Using SmartMesh IP*, in "EWSN 2020 - ACM International Conference on Embedded Wireless Systems and Networks", Lyon, France, February 2020, https://hal.inria.fr/hal-02436263

[26] M. VUČINIĆ, B. SKRBIC, E. KOCAN, M. PEJANOVIC-DJURISIC, T. WATTEYNE. *OpenBenchmark: Repeatable and Reproducible Internet of Things Experimentation on Testbeds*, in "CNERT - IEEE INFOCOM Workshop on Computer and Networking Experimental Research using Testbeds", Paris, France, April 2019, https://hal.inria.fr/hal-02266556

Conferences without Proceedings

[27] A. ABANE, P. MUHLETHALER, S. BOUZEFRANE, A. BATTOU. *Modeling and Improving Named Data Networking over IEEE 802.15.4*, in "IFIP/IEEE PEMWN 2019 : IFIP/IEEE International Conference on

Performance Evaluation and Modeling in Wired and Wireless Networks", Paris, France, November 2019, https://hal.archives-ouvertes.fr/hal-02333795

[28] J. Ammouri, P. Minet, M. Boudiaf, S. Bouzefrane, M. Yacoub. *Self-Organizing Maps Applied to Soil Conservation in Mediterranean Olive Groves*, in "PEMWN2019 - 8th IFIP/IEEE International Conference on Performance Evaluation and Modeling inWired andWireless Networks", Paris, France, November 2019, https://hal.archives-ouvertes.fr/hal-02432848

[29] F. Boukhalfa, M. Hadded, P. Muhlethaler, O. Shagdar. *An active signaling mechanism to reduce access collisions in a distributed TDMA based MAC protocol for vehicular networks*, in "AINA-2019 - Advanced Information Networking and Applications", Matsue, Japan, March 2019, https://hal.archives-ouvertes.fr/hal-02177650

[30] K. Brun-Laguna, P. Minet, Y. Tanaka. *Optimized Scheduling for Time-Critical Industrial IoT*, in "GLOBECOM 2019 - 2019 IEEE Global Communications Conference", Waikoka, Hawai, United States, December 2019, https://hal.archives-ouvertes.fr/hal-02432579

[31] M. Hadded, K. Toumi, A. Laouiti, P. Muhlethaler. *A trust framework for centralized TDMA scheduling mechanism in Vehicular Ad hoc Networks*, in "WTS 2019: Wireless Telecommunications Symposium", New York, United States, April 2019, https://hal.archives-ouvertes.fr/hal-02454384

[32] R. Milocco, P. Muhlethaler, S. Boumerdassi. *Energy-efficient relay selection over fading channels*, in "CCNC 2019 - 16th IEEE Annual Consumer Communications & Networking Conference", Las Vegas, United States, IEEE, January 2019, pp. 1-2 [*DOI :* 10.1109/CCNC.2019.8651688], https://hal.archives-ouvertes.fr/hal-02294729

[33] M. L. F. Sindjoung, P. Minet. *Wireless Link Quality Prediction in IoT Networks*, in "PEMWN 2019 - 8th IFIP/IEEE International Conference on Performance Evaluation and Modeling inWired andWireless Networks", Paris, France, November 2019, https://hal.archives-ouvertes.fr/hal-02432805

[34] A. Sobehy, E. Renault, P. Muhlethaler. *CSI based indoor localization using Ensemble Neural Networks*, in "MLN 2019 : 2nd IFIP International Conference on Machine Learning for Networking", Paris, France, December 2019, https://hal.archives-ouvertes.fr/hal-02334588

[35] A. Sobehy, E. Renault, P. Muhlethaler. *NDR: Noise and Dimensionality Reduction of CSI for indoor positioning using deep learning*, in "GLOBECOM 2019: IEEE Global Communications Conference", Hawaii, United States, IEEE Computer Society, December 2019, https://hal.archives-ouvertes.fr/hal-02314929

Scientific Books (or Scientific Book chapters)

[36] *Machine Learning for Networking: first international conference, MLN 2018, Paris, France, November 27-29, 2018, revised selected papers*, Lecture Notes in Computer Science (LNCS), Springer, Paris, France, 2019, vol. 11407, 388 p. [*DOI :* 10.1007/978-3-030-19945-6], https://hal.archives-ouvertes.fr/hal-02445117

Other Publications

[37] M. Vučinić, G. Selander, J. Mattsson, D. Garcia-Carrillo. *Requirements for a Lightweight AKE for OSCORE*, December 2019, draft-ietf-lake-reqs-00, https://hal.inria.fr/hal-02407621