RESEARCH CENTRE

Paris

2020
ACTIVITY REPORT

Project-Team
EVA

Wireless Networking for Evolving & Adaptive Applications

DOMAIN

Networks, Systems and Services, Distributed Computing

THEME

Networks and Telecommunications

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Project-Team EVA

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

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1 Team members, visitors, external collaborators

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- Miguel Landry Foko Sindjoung [University Conakri]
- Anis Laouiti [Telecom SudParis, HDR]
- Eric Renault [ESIEE]

2 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, for example through standardization and other transfer activities. 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. The Inria team 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 is 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 investigates these two scenarios, as well as centralized and distributed approaches. The work starts with simple 2D models and is 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 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.

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 associate team "REALMS" comprising members from EVA, the University of California in 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

[1] Highway Addressable Remote Transducer

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 works 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 distinguishes 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 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.

4.7 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.

4.8 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.

4.9 MANETs and VANETs

In contrast to routing, other domains in Mobile Ad-hoc NETworks (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.

4.10 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 Deploy, Deploy, Deploy

A performance indicator we use internally in the EVA team is to get our networking technology deployed and used in real-world applications. In 2020, we were able to carry out the following deployments and experiments. For each, we published a video, **click on the links!**

- Real-world test of the BurnMonitor early warning system for wildfires wiyth the Moraga-Orinda Fire Department in California. `https://youtu.be/PDTlyt-wrlE`

- New collaboration with the Besançon Conservatory on wearables for teaching rhythm. https://youtu.be/Auq9sHePRTU
- Deployments of the FrostForecast frost prediction network in a cherry orchard in Chile. https://youtu.be/2y2JsYU-_Vw
- First tests of the HornetTracker system in which we place tags on the back of Asian Hornets to find their nest. https://youtu.be/xG2A21-gCB8 https://youtu.be/CSRxd5wBnFg
- Design of versio 1.1 and 1.2 of the DotBot swarm robotic platform. https://youtu.be/j0S96sSlETg

5.2 Awards

- **Thomas Watteyne** recipient of Analog Devices' Spot Award "in recognition of outstanding effort and contribution", 21 Octobre 2020.
- Spin-off startup Falco recipient of the i-Lab award, the largest Innovation competition for startup companies in France, July 2020.
- **Thomas Watteyne** and Kris Pister (Berkeley) recipient of the France-Berkeley Fund award for the project "m3: Marvelous Micro Mote", May 2020.
- Iman Hmedoush received a best paper award for her paper "Multi-Power Irregular Repetition Slotted ALOHA in Heterogeneous IoT networks" in PEMWN 2020.

5.3 Visibility

News articles on the activity of the team and spin-off company Falco appeared in Midi Libre, Boating Business, Thau Info, Le Telegramme, Ouest France and inria.fr.

5.4 Conference

Paul Muhlethaler was General co-Chair of the IEEE PEMWN 2020 and IFIP MLN 2020 conferences. **Thomas Watteyne** gave keynote addresses to the IOTSMS and IEEE VLSI conferences.

6 New software and platforms

6.1 New software

6.1.1 OpenWSN

Name: 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.

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

Contacts: Thomas Watteyne, Tengfei Chang

Partner: University of California Berkeley

6.1.2 6TiSCH Simulator

Name: 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.

Contacts: Malisa Vucinic, Thomas Watteyne

6.1.3 Argus

Name: 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.

Contacts: Remy Leone, Thomas Watteyne

6.1.4 SolSystem

Name: 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)

URL: http://www.solsystem.io/

Contacts: Keoma Brun-Laguna, Thomas Watteyne

6.1.5 6TiSCH Wireshark Dissector

Name: 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.

Contacts: Jonathan Muñoz, Thomas Watteyne

6.1.6 F-Interop

Name: Remote Conformance and Interoperability Tests for the Internet of Thing

Keywords: Interoperability, Iot, Conformance testing, Standardization

Contacts: Remy Leone, Thomas Watteyne

Partners: UPMC, IMEC, ETSI, EANTC, Mandat International, Digital Catapult, University of Luxembourg, Device Gateway

6.1.7 Mercator

Name: 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.

Contacts: Keoma Brun-Laguna, Thomas Watteyne

6.1.8 py-edhoc

Keywords: Internet of things, 6TiSCH, EDHOC, Python, Security

Functional Description: EDHOC is an authenticated key exchange protocol targeting constrained environments and Internet of Things use cases. This is a Python implementation of the protocol, adapted for use on microcontrollers.

URL: https://github.com/openwsn-berkeley/py-edhoc

Contacts: Timothy Claeys, Malisa Vucinic

6.1.9 EDHOC-C

Keywords: 6TiSCH, EDHOC, Security, Internet of things

Functional Description: EDHOC is an authenticated key exchange protocol targeting constrained environments and Internet of Things use cases. This is a C implementation of the protocol, adapted for use on microcontrollers.

URL: http://github.com/openwsn-berkeley/EDHOC-C

Contacts: Timothy Claeys, Malisa Vucinic

6.2 New platforms

7 New results

7.1 Falco Startup Takes Off

Participants Thomas Watteyne, Trifun Savic, Anna Bednarik, Keoma Brun-Laguna, Jonathan Munoz, Elsa Nicol.

The Falco startup (https://wefalco.com/), which was launched in 2019, has been developing fast in 2020. After winning the Innovation Competition of the 2019 Paris Nautic Show, Falco is recipient of the i-Lab award, the largest Innovation competition for startup companies in France, in July 2020. Falco succesfully closed a first round of investments, at 1 million euros. The Falco solution is now deployed in 7 marinas. Falco now employs 12 people.

7.2 6TiSCH Standardization

Participants Mališa Vučinić, 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 2020, the working group finalized the standardization work, with the publications of 3 standards, 4 additional ones in the process of being published.

7.3 6TiSCH Security

Participants Mališa Vučinić, Timothy Claeys, Thomas Watteyne.

The security work of Inria-EVA is a continuation of the efforts started during the H2020 ARMOUR project. The work has initially focused on designing the "Minimal Security" solution that has been approved to be published as an RFC in 2019.

In 2020, Inria-EVA participated in the standardization of two draft standards in the ACE working group on security. Both draft standards are technically linked to the LAKE-EDHOC protocol being standardized in the LAKE working group, and their envisioned use cases are 6TiSCH networks.

We published 3 versions of a draft standard on lightweight authorization for authenticated key exchange [49], complementing the EDHOC protocol with 3rd party authorization information. We also published 2 versions of a draft standard on certificate enrollment [50]. Both of these documents were presented to the ACE working group during the IETF 109 online meeting. We plan on continuing the work on these documents in 2021 and implement them in the context of our in-house testbed.

7.4 6TiSCH Benchmarking

Participants Mališa Vučinić, 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 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 IETF LAKE Standardization

Participants Mališa Vučinić, Timothy Claeys, Thomas Watteyne.

IETF LAKE working group, formed in late 2019, aims at standardizing a lightweight authenticated key exchange protocol for IoT use cases. The group is co-chaired by , Mališa Vučinićof Inria-EVA.

LAKE working group has held a total of 5 meetings in 2020. In 2020, Inria-EVA finalized the work on collecting the requirements for standardizing a LAKE protocol [51], by publishing 4 revisions of the document.

With our in-house implementations of the LAKE-EDHOC protocol in Python and in C, Inria-EVA participated in two interop test events organized online. Our implementations successfully interoped with other implementations based on the LAKE draft standard.

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.

7.7 Centralized or Distributed Scheduling for IEEE 802.15.4e TSCH networks

Participants Yasuyuki Tanaka, Pascale Minet, Thomas Watteyne, Mališa Vučinić, Tengfei Chang, Keoma Brun-Laguna.

The wireless TSCH (Time Slotted Channel Hopping) network specified in the 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

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.

7.8 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 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.

7.9 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.

7.10 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 was published in the Sensors journal in 2019.

7.11 Machine Learning applied to Networking

7.11.1 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 try 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.

Evaluating the upper bound of energy cost saving by proactive data center management

In [20], we evaluate evaluate the energy cost savings that can be achieved by a proactive DC management. Such a management consists in periodically configuring the DC by turning some servers on or off to provide an amount of energy equal to the sum of i) the predicted energy to serve the user requests that will arrive in the next period, and ii) the energy needed to correct the error on the prediction made for the previous period. The predicted energy has a proactive cost, whereas the corrective energy has a reactive cost. Two predictors are proposed: a linear one based on the ARMA model and a nonlinear one using the conditional probability density function. These predictors maximize the relative energy cost saving.

We determine the tight upper bound of the relative energy cost savings valid in all cases. Knowing the upper bound makes it possible to decide on the suitability or not of using proactive action. If a choice must be made between different possible proactive strategies, both costs and savings change. Therefore, this paper proposes a methodology that helps to choose the best strategy (i.e. that maximizes the savings) between possible proactive strategies.

The methodology proposed is generic and can be applied to any DC that meets the assumptions made in this paper. These assumptions are realistic and can be met by many data centers. As an example, we have used the data set collected over 29 days in an operational data center of Google. By applying this methodology on the Google data, an improvement up to 85% can be obtained, leaving room for multiple optimizations. The relative energy cost saving that depends on the DC considered have been computed. Using the predictors analyzed with this data set, we find that the relative saving of the proactive action increases when the proactive cost of one Joule becomes negligible compared to the reactive cost. This would make it possible to decide between possible proactive action strategies in this Google DC.

Proactive Data Center Management Using Predictive Approaches

Data Center (DC) management aims at promptly serving user requests while minimizing the energy consumed. This is achieved by periodically turning off unnecessary servers to save energy and adapting the number of servers that are on to the time-varying and heterogeneous user requests. A great change in the number of servers on leads to a considerable management effort, also called control effort in the literature, which should be reduced as much as possible. Since feedback control can improve the performance of computing systems and networks, we propose to use it in [21] to achieve this dynamic capacity provisioning of the DC. In order to design this feedback control, first, we develop a dynamic model of the DC. The purpose is to design a feedback control strategy based on the DC model, able to optimize i) the Quality of Service, ii) the energy consumed and iii) the management effort.

Second, we compare three DC control strategies. The first one, Reactive Control (RC), is an open-loop control which provides the energy requested in the previous period. Consequently, it provides the exact amount of energy requested, which makes it energy efficient, but with a big large latency, leading to a significant scheduling delay. The second one, Reactive Feedback Control (RFC), is a closed-loop strategy; it needs to measure the service on-line. It uses the accumulated error from the previous period to decide the provisioning period allowing the requests to be served in less than two time periods, but is not energy efficient. The third one is Model Predictive Control (MPC) which is a feedback control and is also proactive, since it uses prediction of the demand. MPC is an optimal solution between weighted error and control effort.

From the comparison of these three control strategies applied to the traces of a real DC, three conclusions can be drawn:

1. The proposed optimal proactive MPC, that simultaneously minimizes the waste of energy with maximum possible QoS by managing the control effort, significantly improves reactive open-loop control. This scheme achieves scheduling times of the order of 10% of those used by reactive control while only increasing the energy used by 10%. It is important to note that this reduction is the maximum possible with this type of proactive scheme since the design is optimal.
2. DC dispatch time is shown to affect Quality of Service in all three control settings, but not energy savings, which remain almost the same as RC energy efficiency.
3. It is shown that when the control effort is not taken into account, the same optimal performance as in MPC is obtained using RFC.

7.12 Protocols and Models for Wireless Networks

7.12.1 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.

Irregular Repetition Slotted Aloha (IRSA) with multi-power

Irregular Repetition Slotted Aloha (IRSA) is one candidate member of a family of random access protocols to provide solutions for massive parallel connections in the Internet of Things (IoT) networks. The key features of this protocol are repeating the transmitted packets several times and using Successive Interference Cancellation (SIC) at the decoder to re-solve the collisions, which dramatically increases the performance of Slotted ALOHA. Motivated by multiple previous studies of IRSA performance in different settings, we focus on the scenario of an IoT network where the packets of different nodes are received with different powers at the base station, either per design due to different transmission powers, or induced by the fact that the nodes are at different distances from the base station. In such a scenario, the capture effect emerges at the receiver, which in turn enhances the protocol performance. We analyze the protocol behavior using a new density evolution which is based on dividing nodes into classes with different powers. By computing the probability to decode a packet in the presence of the interference, we explore the achievable throughput and its associated gain and show the excellent performance of Multi-Power IRSA.

In [38], we formally introduced multi-power IRSA (MP-IRSA), as a random access method, when the replicas of different users are transmitted/received with different powers. We introduced a new density evolution variant based on group-ing users into classes: it allows analyzing the performance of MP-IRSA. Multi-power IRSA proves to be a better choice than CRDSA and classical IRSA and confirms the benefits of effects of the capture effect at the receiver. The impact of different system factors on the achieved throughput and the associated load was extensively studied. First, the power difference between the classes and the number of classes plays a huge role in the decoding process, and we observe the best results when the power difference is large: decoding is cascading (one class after the other), instead of cycling (switching between different classes). The receiver sensitivity and the density of each class are other important factors that we studied. Another key factor that we did not explore is the repetition degree distribution: we used the same soliton distribution for all classes. Finding methods to optimize a common degree distribution for all classes or multiple degree distributions for multiple classes, and studying its impact, is apossible future work.

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

In [43] we studied one of the modern random access protocols: Irregular Repetition Slotted Aloha (IRSA) in its frameless version. We adapted a reinforcement learning approach based on Regret Minimization to optimize the transmission strategy of this protocol, and thus proposed the protocol “IRSARM”. RM is well suited to IRSA, as in both cases, one uses a set of probabilities of selecting a given number of repetition. The learning is performed offline: it learns the main protocol parameters (the user degree distribution) for a set of predefined network loads. After the learning phase, the parameters can be later used in a network: assuming that the estimate of the load is broadcast by the base station, each device will select the set of parameters that were learned with the closest load. We detailed precisely the mapping between our problem, optimizing IRSA, and the centralized learning approach with RM, including delayed updates, reward computation, and alternate simulations, the introduction of priority classes, etc. Simulation results show a very high level of performance of IRSA when it is optimized with Regret Minimization, and how IRSA-RM behaves for different types of actions (degrees) sets. Future work will include considering richer actions, more sophisticated RM techniques such as CFR, and applying Deep Reinforcement Learning techniques.

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.

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

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

Indoor Localization has attracted interest in both academia and industry for its wide range of applications. In [41] we propose an indoor localization solution based on Channel State Information (CSI). CSI is a fine-grain measure of the effect of the channel on the transmitted signal. It is computed for each subcarrier and each antenna in the Multiple-Input Multiple-Output (MIMO) antenna case. It is also becoming a trend for indoor position fingerprinting. By using a K-nearest neighbor learning method a highly accurate indoor positioning is achieved. The input feature is the magnitude component of CSI which is preprocessed to reduce noise and allows for a quicker search. The euclidean distance between CSI is the criteria chosen for measuring the closeness between samples. The method is applied to a CSI dataset estimated at an 8×2 MIMO antenna that is published by the organizers of the Communication Theory Workshop Indoor Positioning Competition. The first step consisted of choosing the input feature from the CSI components: real, imaginary, magnitude, or phase. We used a statistical analysis to show that the magnitude is the most stable component, therefore, we selected it as the input feature. Magnitude values are then reduced using a polynomial line of degree 6 and least-squares optimization. Out of the 924 magnitude points, 33 equidistant points were chosen to represent the magnitude component. The Euclidean distance has then been used to represent the closeness between magnitude samples. With a k value equal to one, a k-nearest neighbor search was conducted over the training set for each test sample. The proposed method is compared with three other methods all based on deep learning approaches and tested with the same dataset. The K-Nearest Neighbor method presented in [41] achieves a Mean Square Error (MSE) of 2.4 cm which outperforms its counterparts.

7.12.3 Energy efficient forwarding in sensors networks

Participants Ruben Milocco (Comahue University, Argentina, invited professor), Paul Muhlethaler, Selma Boumerdassi (Cnam).

In [22] we have presented three designs for energy efficient transmission in a sensor network under shadow fading channels based on minimal energy consumption. The first is when both the transmission rate and power can be tuned. In the second and third, only the transmission power or the transmission rate is tuned. The criterion is based on computing the outage probability of the information to reach the next hop. The two sub-optimal controlled strategies perform similarly to the optimal, but we have analytically demonstrated that the rate-control is closer to the optimal than the power control. In the optimal case, PR-control, the minimization is performed for a fixed period of time. This implies that for a given amount of information that needs to be sent it is possible to fix the interval delay time with minimum energy. However, in both sub-optimal designs, the time interval time is not fixed but varies very close around the value of the optimal design. In order to evaluate the improvements, simulations were performed using two fading distributions, the Log-normal and the Nakagami and comparing with the case in which the rate and power are fixed. The results shows that even in the case with best possible fixed values of P and R, performances can be improved by up to ten times. Finally, we leave for future work a robust energy efficient design that does not require knowledge of the probability distribution of fading.

7.12.4 Deployment of Named Data Networking in the Internet of Things

Participants Amar Abane, Samia Bouzefrane, Soumya Banerjee, Paul Mühlethaler.

In [8] we have investigated how to take advantage of NDN for the IoT in a simple and feasible solution. To that purpose, a realistic NDN-IoT architecture has been designed and realized considering the IEEE 802.15.4 wireless technology. After identifying the integration of NDN in the low-end IoT as the most realistic approach, the main integration issues have been discussed, and some mechanisms have been proposed. The proposed mechanisms show the flexibility of NDN to support low rate lossy technologies such as the IEEE 802.15.4. The NDN-IoT architecture proposed aims to shape a novel and strong NDN-IoT duo. Moreover, lightweight NDN forwarding in wireless networks with broadcast has been investigated. The objective through the forwarding approach proposed is to show that broadcast can be used successfully in constrained networks, while ensuring reduced overhead and accurate forwarding decisions. For that, we have designed R-LF; a forwarding strategy based only on content names and broadcast without any host identification. R-LF is a reactive forwarding strategy that does not require additional communication to maintain forwarding information. Results obtained show that R-LF is able to provide efficient data retrieval using exclusively the content-centric paradigm of NDN, without any host identification such as logical or link-layer addresses. The deployment evaluation provides some preliminary measurements and empirical comparison with IP-based solutions. For example, the deployment may show the lightweight and simplicity of NDN implementations for IoT. Overall, the main limitation we may identify in this work is the lack of direct performance comparisons between NDN and IP. Although it could be useful, this can be explained by several reasons. First, we greatly rely on the discussions about IP limitations and NDN native features to show the superiority of NDN, which is indisputable in many aspects such as security, native caching and simplicity. Second, when comparing IP and NDN in a given scenario, the fairness of the configurations is frequently questioning, for example when enabling caching.

7.12.5 Design and Evaluation of a Flooding-Based Location Service in Vehicular Ad Hoc Networks

Participants Paul Mühlethaler, Eric Renault, Selma Boumerdassi.

SFLS, the semiflooding location service, an efficient and yet simple solution for the dissemination of location information in VANETs, is described in [23]. We have analyzed the performance of this protocol with a uniform Poisson point process of nodes in 1D, 2D, and 3D networks. Even though the basis of this protocol is a broadcast scheme, we have shown that the number of messages per update remains very low. For different cases, we built an analytical model to upper bound the number of messages per update, and carried out simulations to verify our computations. The matching of the analytical model and the simulations was very good. We have also compared SFLS with the broadcast optimization scheme of OLSR: the multipoint-relay technique. We have presented two case studies where SFLS and the multipoint-relay technique performed differently. In dense or very dense networks, the MPR scheme was better, but SLFS outperformed the MPR flooding of OSLR in sparse or moderately dense networks, and in any case, when the number of hops was large. It would be interesting to combine SFLS with a location-prediction technique based on node kinematics to refine their positions between the reception of two consecutive SFLS updates. This idea could be the starting point for further studies.

7.12.6 LoRA Models

Participants Rahim Haiahem, Pascale Minet, Selma Boumerdassi (Cnam), Leila Azouz Saidane (invited professors).

High accuracy air pollution monitoring in a smart city requires the deployment of a huge number of sensors in this city. One of the most appropriate wireless technologies expected to support high density deployment is LoRaWAN which belongs to the Low Power Wide Area Network (LPWAN) family and offers long communication range, multi-year battery lifetime and low cost end devices. It has been designed for End Devices (EDs) and applications that need to send small amounts of data a few times per hour. However, a high number of end devices breaks the orthogonality of LoRaWAN transmissions, which was one of the main advantages of LoRaWAN. Hence, network performances are strongly impacted.

An Orthogonal Air Pollution Monitoring Method (OAPM) Based on LoRaWAN

To solve this problem, we propose a solution called OAPM (Orthogonal Air Pollution Monitoring) which ensures the orthogonality of LoRaWAN transmissions and provides accurate air pollution monitoring. In [16], we show how to organize EDs into clusters and sub-clusters, assign transmission times to EDs, configurate and synchronize them, taking into account the specificities of LoRaWAN and the features of the air pollution monitoring application. OAPM is a LoRaWAN-based architecture for monitoring air pollution. The system behavior includes four phases after the deployment: (1) the Joining phase where the ED joins the LoRaWAN network, (2) the Configuration phase where the ED is assigned its configuration parameters (e.g., Synchronization Period, Monitoring Period, number of Monitoring Periods per Synchronization Period, Transmission Window, Transmission Time), (3) the Synchronization phase where the ED is synchronized to the clock of the gateway, which is the reference time in LoRaWAN, and (4) the Monitoring phase where the EDs send their pollutant report to the gateway and sleep until their next transmission period or the next Synchronization Period, when they repeat the transmission process.

Potential applications are various including air pollution monitoring, smart farming, environment monitoring. They would benefit from OAPM advantages which are the following:

- It supports of a high number of EDs while maintaining a PDR close to 1, provided a number of receive paths > 6.
- It has a low energy consumption, because all transmissions are scheduled by the network server.
- It provides a high network lifetime.
- It is fully compliant with the requirements expressed by the World Health Organization and the US Environmental Agency for air pollution monitoring.
- It is a simple solution based on an implicit clustering of EDs according to their geographic coordinates and the computation of their transmission times by the Network Server.

OAPM has been implemented and simulations were conducted using the NS3 simulator. By comparing OAPM with other proposed strategies in the literature, we found that OAPM ensures orthogonality between transmissions while supporting large-scale networks. However, the non-deterministic selection of the frequency channels introduces a slight drop in the performances. This happens when several EDs belonging to the same sub-cluster share the same frequency channel. As a further work, we intend to introduce a new solution enabling a collision-free sharing of frequencies between EDs. This amendment will be combined with the proposed OAPM to ensure high-level performances and create a scalable air pollution monitoring solution.

Collision-Free Transmissions in an IoT Monitoring Application Based on LoRaWAN

With the Internet of Things (IoT), the number of monitoring applications deployed is considerably increasing, whatever the field considered: smart city, smart agriculture, environment monitoring, air pollution monitoring, to name a few. The LoRaWAN (Long Range Wide Area Network) architecture with its long range communication, its robustness to interference and its reduced energy consumption is an excellent candidate to support such applications. However, if the number of end devices is high, the reliability of LoRaWAN, measured by the Packet Delivery Ratio (PDR), becomes unacceptable due to an excessive number of collisions. In [17], we propose two different families of solutions ensuring collision-free transmissions.

The first family, called OAPM, is TDMA (Time-Division Multiple Access)-based. All clusters transmit in sequence and up to six end devices with different spreading factors belonging to the same cluster are allowed to transmit in parallel. OAPM_O is an optimized variant of OAPM_D using several frequency channels per cluster to allow several Eds with the same spreading factor to transmit in parallel.

The second family, called FAPM, is FDMA (Frequency Divsion Multiple Access)-based. All clusters transmit in parallel, each cluster on its own frequency. Within each cluster, all end devices transmit in sequence. FAPM_O is an optimized variant of FAPM allowing several EDs of the same cluster to transmit in parallel.

These solutions have been evaluated theoretically and by simulation with NS3 in various configurations, uniform or not, with some or all spreading factors present in the monitoring area, different numbers of frequency channels, and different sizes of the monitoring period. Their performance are compared in terms of PDR, energy consumption by end device and maximum number of end devices supported. The simulation results show that all these solutions ensure that no messages are lost due to collisions. They corroborate the theoretical results of the maximum number of EDs supported by each solution: FAPM_O supports the highest number of EDs, because of its better use of the frequency channels available. FAPM outperforms OAPM_D, whereas OAPM_O improves OAPM_D when all SFs are not present. Finally, a hybrid solution, FAPM_H, is proposed. It combines FAPM and OAPM to achieve both inter-channel parallelism and intra-channel parallelism while minimizing the data gathering duration. This is done by maximizing the parallelism of transmissions under the constraints given by the maximum number of available frequency channels and the maximum number of messages the gateway is able to demodulate simultaneously. The complexity of solving this optimization problem is left to the Network Server.

As a further work, the evaluation of FAPM_H and its comparison with other schemes will be carried on. The proposed solutions will be implemented on real testbeds. They will also be tested in different use case applications to confirm their effectiveness. More generally, the coexistence of several IoT applications with heterogeneous requirements in the same LoRaWAN gateway is a challenging study.

7.13 Vehicular Ad-hoc NETworks (VANETs)

7.13.1 Combining random access and TDMA scheduling strategies for vehicular ad hoc networks

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

AS-DTMAC : Active Signaling-Distributed Time Division Multiple ACcess

This work is based on Fouzi Boukhalfa's PhD which started in October 2018. 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. We show 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.

In [11] we present an analytical model for studying the performance of the AS-DTMAC protocol. We use recursive equation on generating functions to obtain the probability of collision. Two cases of the arrival process in AS-DTMAC have been investigated and modeled. In the first case, the packets from the vehicles arrive in each time slot according to a homogeneous Poisson process, whereas in the second case there is a burst of arrivals for very urgent messages. To make our analytical model as complete as possible, we introduce error into the model during the selection process. We define two kinds of error that can occur in the detection process: vehicles can either miss a transmission or sense a false transmission. With the first kind of error, the performance remains very good, even with up to 5whereas with the second kind of error, the selection may end up with no transmission on the payload slot, which is much more detrimental to the whole performance. The simulation results confirm the validity of the analytical model and show that AS-DTMAC very significantly outperforms the DTMAC protocol in terms of collision probability. The transmission of urgent packets is also very efficient in AS-DTMAC. In future work, we plan to precisely evaluate the probability of the error in the detection of bursts in order to optimize the active signaling process. Furthermore, we plan to investigate the idea of no longer considering that the CSMA-based MAC protocols and TDMA based MAC protocols are competitors. By combining the two techniques, the drawbacks of contention based-access in the former and resource reservation in the latter can be overcome. Such an application could be the future Wi-Fi standard for vehicles (IEEE 802.11bd), which requires ensuring a backward compatibility mode (to make communication possible between vehicles using IEEE 802.11p and vehicles using the new communication technologies (IEEE 802.11bd). Proposing this kind of protocol will be beneficial: the CSMA/CA will keep communication with older nodes (IEEE 802.11p) possible, while AS-DTMAC will enable low latency access.

Coexistence AS-DTMAC - IEEE 802.11

In [33] we have shown that the contention-based IEEE 802.11p protocol can coexist with the contention-free AS-DTMAC protocol. We have studied the probability that an IEEE 802.11p transmission can interfere with the AS-DTMAC selection process and to preempt an AS-DTMAC transmission. This probability is very small, indicating, on the one hand, that an AS-DTMAC transmission is very unlikely to be preempted by an IEEE 802.11p transmission. On the other hand, when IEEE 802.11p transmissions are established, the AS-DTMAC, being a TDMA system, can not in principle preempt the transmission. We have studied the distribution of the waiting time for an AS-DTMAC user to be able to access to the channel. We have shown that, if needed, AS-DTMAC can possibly preempt the flow of IEEE 802.11p transmissions if AS-DTMAC operates asynchronously. In this case, the AS-DTMAC user has only to transmit just after the IEEE 802.11p transmission. If we use this operating mode, AS-DTMAC has priority over IEEE 802.11p transmissions. Moreover, the first bit of the transmission key in AS-DTMAC allows one to prioritize access for AS-DTMAC users. A fairness index showing the ability of IEEE 802.11p devices to have the same opportunities as NGV devices to access the channel will be the subject of another contribution. Also, the model assumes a perfectly symmetric transmission (reception) range situation. Therefore, it would be interesting to show how an asymmetric scenario would affect the coexistence of the two protocols. Moreover, we plan to continue to investigate the other specifications required for the design of the IEEE 802.11bd, such as the ability of NGV devices to run in a mode in which they can interoperate with IEEE 802.11p devices, a property that is defined in the literature such as the Backward compatibility.

Study of the signaling bursts of AS-DTMAC

In [32] the exact definition of the signaling burst of AS-DTMAC was proposed with the computation of miss detection in the selection process, by using a detection model based on GLRT. We estimate that the minimum length of preamble required for the active signaling process is 3 OFDM symbols. We show that the active signaling part of the slot in AS-DTMAC must encompass 8 mini-slots and thus the signaling burst will last 4.8µs. This proposed configuration will optimize the time left for the payload part of the packet, resulting in increased throughput compared to that proposed in [1]. This study takes into account the structure of the physical layer of the current IEEE 802.11p standard. Therefore, this is makes it well-suited to the next generation of IEEE 802.11bd proposal. The good performance of GLRT shown in [32], motivates us to further investigate the robustness of this algorithm in real implementations, using GNU Radio Software and USRP units. Implementing this kind of detector in the receiver will significantly enhance the reliability of the communication.

7.13.2 Cross-layer routing in VANETs

Survey of MAC-aware Routing Protocols for Vehicular Ad Hoc Networks

Participants Abir Rebei (Hatem Bettahar IResCoMath Research Unit, Tunisia), Mohamed Hadded (Vedecom), Haifa Touati (Hatem Bettahar IResCoMath Research Unit, Tunisia), Fouzi Boukhalfa (Vedecom), Paul Mühlethaler.

The constantly growing number of vehicles on our roads has become an increasing major cause of serious injury and death. Efficient data dissemination in Vehicular Ad hoc Networks (VANETs) inevitably requires an efficient and robust routing protocol. In this context, several categories of routing protocols have been proposed in the literature to meet VANETs application requirements in terms of delay, packet loss and throughput. In [40], we focus on cross layer routing protocols. We present a survey of state-of-the-art MAC aware routing protocols designed for VANETs. These solutions can broadly be divided into two categories: contention-free and contention-based MAC-aware routing. In this paper we carryout a comprehensive comparison of these approaches. Finally, we identify open research issues that should be addressed in order to improve MAC aware routing techniques in VANETs. Given emphasis on road safety in VANETs, designing a reliable and robust MAC routing protocol seems essential for ensuring efficient communications and reliable message dissemination. A major challenge lies in combining functionalities of different layers in order to enhance network performances. This paper, which presents an overview of MAC aware routing protocols based on contention-free, contentionbased or hybrid scheme, also shows the performance of these protocols in meeting VANET requirements. In this paper, we have discussed the cross-layer concept and its role in designing routing protocols and investigating goals in terms of QoS, road safety and mobility management by considering the benefits of mixing different functionalities of different layers. Then, we have focused on some proposed MAC routing protocols based on the TDMA and CSMA/CA technique. Furthermore, we have examined these protocols through a classification and comparison conducted according to certain features and metrics performances. This comparison is intended to provide a better understanding of these protocols. Finally, we have presented some challenges for VANETs that should be addressed in design of new Mac routing protocols. To the best of our knowledge, the paper represents the first attempt that gives an overview on the MAC aware routing protocols proposed for VANET.

Trust aware cross-layer routing in VANETs

Participants Sihem Baccari (Hatem Bettahar IResCoMath Research Unit, Tunisia), Mohamed Hadded (Vedecom)), Haifa Touati (Hatem Bettahar IResCoMath Research Unit, Tunisia) , Paul Mühlethaler.

In [9], we have proposed a trust model for securing VANETs against Black-hole, Gray-hole and MAC attacks within the TRPM cross-layer routing protocol. The proposed solution, called Trust-based TRPM, has proven to have considerable capacity in detecting and eliminating malicious nodes that attempt to disrupt normal network operation. Moreover, Trust-based TRPM is a very fast technique which does not require much computing time as each node is responsible for its safety, thereby avoiding the need to load the network. Simulation results illustrate the effectiveness of the proposed trust-based approach to detect and isolate misbehaving nodes. In summary, we have demonstrated that our solution improves the PDR and channel access rate when different ratios of malicious nodes are present in the network. Our present solution is intended for detecting some sets of malicious behavior. In future work we aim to improve and expand our mechanism to include other types of attacks and malicious activities. In particular we will focus on the detection of packet transfer delay attacks, which threaten the reception delays and represent one of the major constraints for real-time security applications.

Performance Impact Analysis of Security Attacks on Cross-Layer Routing Protocols in VANETs

Participants Sihem Baccari (Hatem Bettahar IResCoMath Research Unit, Tunisia), Mohamed Hadded (Vedecom)), Haifa Touati (Hatem Bettahar IResCoMath Research Unit, Tunisia) , Paul Mühlethaler.

The highly dynamic nature of vehicular networks not only makes their configuration and set up difficult, but also makes them very vulnerable to attack, especially with the absence of a central control. Therefore, in order to make VANETs more secure, it is essential to study and assess the impact that attacks can have on data dissemination in these networks. In [30] we have identified the most serious attack models and have used simulation to assess their impact on the TRPM cross-layer protocol. We have identified several previously undocumented vulnerabilities which threaten the time slots scheduling process of TRPM. In addition, we have demonstrated through different attack models, the extent of the damage that these vulnerabilities can lead on the performance of the TRPM protocol. The simulation results show the severity of these attacks, on the performance of TRPM in terms of Packet Delivery Ratio, which drastically decreases to 13under the effect of Black-hole attack. The End-to-End Delay evaluation reveals the presence of Black-hole and Gray-hole attackers in the network increases the transmission delay up to 1.8s which exceeds the acceptable threshold for a number of delay-sensitive VANET applications. Finally, exploiting the slot scheduling vulnerability that we identified reveals that up to 47% of free slots could not be reserved due to MAC attack which means that 1/2 of channel capacity is wasted. In future work, we will exploit the results of this investigation, to develop a solution for detecting and preventing attacks threatening the TRPM protocol. Mainly we will focus on the new identified MAC level attacks to provide a solution against these types of malicious behavior.

7.13.3 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. In https://doi.org/10.1016/j.eswa.2020.113855 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.

7.14 Graph-Based Subjective Matching of Trusted Strings and Blockchain-Based Filtering for Connected Vehicles

Participants Mamoudou Sangare, Soumya Banerjee, Paul Mühlethaler, Thinh Le Vinh (Ho Chi Minh City University of Technology and Education (HCMUTE)).

In [44] a message matching model and the conceptual level of graph referencing blockchain have been proposed. The model can filter the trusted and untrusted messages in connected car scenarios, analogous to a conventional blockchain mechanism. However, as participants proceed with a voting mechanism, unwanted delay and self-biasing can be introduced in the process. In order to avoid that, a distributed blockchain consensus voting mechanism for any decision taken with respect to trust evaluation is used, this method can be more feasible for collective decisions. This paper has more open research issues challenging the blockchain mechanism. This is because the security is questionable due to group and collective decision-making and repeat occupancy of the message. This is equivalent to a double spending attack in normal blockchain. As a future extension, therefore, a DAG (Direct Acyclic Graph) and the descendants can be integrated in the block-chain, consolidating its security and spoofing mechanism.

7.15 Developing Customized and Secure Blockchains with Deep Federation Learning to Prevent Successive Attacks

Participants Soumya Banerjee (Trasna-Solutions, Ireland), Soham Chakraborty (KIIT, Bhubaneshwar), Paul Mühlethaler.

The main objective of [31] was to detect an attack in a blockchain network using federated learning embedded with a sequential auto-encoder model. As attacks are very rare among many transactions, it is very difficult for anyone to label them manually. We considered an unsupervised learning mechanism in a distributed framework. The proposed model can be used to detect successive attacks beforehand with the master-client mechanism of the federated learning system. In a distributed manner, the model is trained on several client machines and after every interval, the weights of the master model are updated. As soon as any transaction falls as an outlier, it is predicted to be an attack or a suspicious transaction. Using LSTM instead of generic RNN for our training algorithm, we reduce the possibility of vanishing and exploding gradient as the amount of data is large. The sequence-to-sequence deep learning model helps to capture the underlying probability distribution for normal consistent transactions. The work has manifold future possibilities to integrate ML algorithms in blockchain processes. It is worth investigating deep learning deployment for energy perspectives blockchain. Therefore, the parallel mode and optimized approach of block mining time with the detection of suspicious blocks might lead to sound synchronization of blockchain process and such distributed machine learning interfaces.

8 Bilateral contracts and grants with industry

8.1 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. Trifun Savic is doing his PhD under a CIFRE agreement between Inria and Wattson Elements.

9 Partnerships and cooperations

9.1 International initiatives

9.1.1 Inria International Labs

REALMS

Title: *REALMS*

Duration: 2015 - 2020

Coordinator: Thomas Watteyne

Partners:

- Civil and Environmental Engineering, University of California Berkeley (United States)

Inria contact: Thomas Watteyne

Summary: During the 2015-2017 period, the REALMS associate team has collected what is arguably the largest networking statistics dataset for TSCH networks, a networking technology developed by Inria. This dataset is being collected through 21 networks (over 1,000 sensors) deployed in 4 continents. This dataset is a goldmine for understanding the applicability and limits of TSCH technology. The goal of the REALMS associate team, which brings together networking specialists, data scientists and application experts, is threefold. First, we model the dependability of TSCH networks, for example in the trade-off between power consumption and latency/ Second, we develop a tool to compute where to best position repeater nodes when deploying such a network, cutting down deployment time from days to hours. Finally, we further develop our complete Sensor-to-Cloud, and explore its applicability to fields such as Smart Agriculture. The REALMS associate teams bring together the EVA team at Inria-Paris, the Glaser team at UC Berkeley, and the Kerkez team at UMichigan.

9.1.2 Inria international partners

The EVA team has been building up a very strong partnership with Inria Chile, through the FrostForecast project.

9.2 European initiatives

9.2.1 FP7 & H2020 Projects

- H2020 SPARTA, Jan 2019 - Jan 2022. A cyber-security excellence network throughout Europe. **Mališa Vučinić** leads Inria-EVA participation.

9.3 National initiatives

9.3.1 Inria Project Labs, Exploratory Research Actions and Technological Development Actions

- RIOT-fp IPL, 2019-2022. RIOT-fp is an Inria Project Lab on cyber-security targeting low-end, microcontroller-based IoT devices, which run operating systems such as RIOT and a low-power network stack such as OpenWSN. **Mališa Vučinić** is lead.

- ATT FrostForecast, 2020-2021. Deploy a frost forecast system in orchards in Chile, with Inria Chile. Said Alvarado is lead.

- ADT 6TiSCH, 2018-2020. Benchmark the performance of 6TiSCH under realistic scenarios, through experimentaion using the OpenTestbed. Tengfei Chang is lead.

9.3.2 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.

9.3.3 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.

10 Dissemination

10.1 Promoting scientific activities

10.1.1 Scientific events: organisation

General chair, scientific chair **Paul Muhlethaler** was General Co-Chair of MLN 2020 (24-25 November 2020 remote conference). During this conference three key-notes where given. Merouane Debbah presented "The rod beyong 5G", Philippe Jacquet presented "Toward a theory of learnability: The algorithms and the frontiers of Artificial Intelligence" and Fakhri Karray :"Next Frontiers in Smart Mobility". Twenty five (25) technical papers were also presented during six sessions. Revised Selected Papers of MLN 2019 were published in [45].

Paul Muhlethaler was General Co-Chair of PEMWN 2020 (1-3 December 2020 remote conference). During this conference three tutorials where given. Alexandre Abadie, Inria, Saclay preseneted "Micro-controller based secure IoT: a Hand-on Course". Sonia Mettali, ISAMM, Tunisia presented "When routing meets caching in NDN". Hella Ben Ayed, FST, Tunisia presented "Cyber security, trust and privacy: What role can the Blockchain play". Sixteen technical (16) papers were also presented during six sessions. Best paper awards were given to two very good technical papers.

Reviewer

- **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.
- **Mališa Vučinić**
  - Elsevier Pervasive and Mobile Computing
  - IEEE Access
  - IEEE Internet of Things Journal
  - Wiley Internet Technology Letters
  - IEEE Transactions on Cloud Computing
  - Elsevier Computer Communications
- 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)

10.2 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 Dominique Barthel. Spring 2020.
- **Thomas Watteyne** teaches 1/2-day crash course on the Industrial IoT, Telecom ParisTech. Graduate level. 24 September 2020.
- **Mališa Vučinić** teaches 6-week course on IoT, with associated hands-on labs. Graduate level. ESME Sudria. Dec 2019 - Jan 2020.

10.2.2 Supervision

- PhD : Fouzi Boukhalfa, Low and high reliability access in Vehicular Ad-hoc NETworks. Sorbonne University. **Paul Muhlethaler**.
- PhD (ongoing) Trifun Savic, Indoor localization, Sorbonne University. **Thomas Watteyne**, under a CIFRE agreement with Wattson Elements, France.
- PhD (ongoing) Razanne Abu Aisheh, Robotics, Sorbonne University. **Thomas Watteyne**, under a CIFRE agreement with Nokia Bell Labs, France.
- 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 (Defense in November 2020) Abdallah Soheby, Localisation basée sur l'apprentissage artificielle en 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

- PhD:
  - **Thomas Watteyne** member of the examination board PhD thesis of Vasileios Kotsiou. Doctoral work on "Reliable Communications for the Industrial Internet of Things" done at the University of Strasbourg, France, under the supervision of Georgios Z. Papadopoulos, Periklis Chatzimisios and Fabrice Theoleyre. Viva on 25 September 2020.

– **Thomas Watteyne** member of the examination board PhD thesis of Jan Bauwens. Doctoral work on “Sustainable and Interoperable MAC Protocol Design for Heterogeneous Internet of Things Systems” done at the University of Ghent, Belgium, under the supervision of Eli De Poorter and Ingrid Moerman. Viva on 17 November 2020.
– **Thomas Watteyne** member of the examination board PhD thesis of Abdulkadir Karaağaç. Doctoral work on “Advanced IoT: Achieving Improved Interoperability and Dependable Connectivity for Complex IoT Systems” done at the University of Ghent, Belgium, under the supervision of Jeroen Hoebeke and Eli De Poorter. Viva on 15 May 2020.
– Adallah Sobehy. “Localisation basée sur l’apprentissage artificielle en 5G.” Institut Polytechnique de Paris, Nov. 6, 2020 **Paul Muhlethaler** examiner

10.3 Popularization

- **Mališa Vučinić** contributed to Inria’s work-in-progress whitepaper on Internet of Things security.

11 Scientific production

11.1 Major publications

[1] F. Boukhalfa, M. Hadded, P. Muhlethaler and O. Shagdar. ‘Performance Evaluation of an Active Signaling based Time-Slot Scheduling Scheme for connected vehicles’. In: *Annals of Telecommunications - annales des télécommunications* (2020). URL: https://hal.archives-ouvertes.fr/hal-02981063.

[2] T. Chang, T. Claeys, M. Vučinić, X. Vilajosana, T. Yuan, B. Wheeler, F. Maksimovic, D. Burnett, B. Kilberg, K. Pister and T. Watteyne. ‘Industrial IoT with Crystal-Free Mote-on-Chip’. In: *IEEE Symposia on VLSI Technology and Circuits (VLSI)*. Honolulu, HI / Virtual, United States, June 2020. URL: https://hal.inria.fr/hal-02916078.

[3] T. Chang, T. Watteyne, F. Maksimovic, B. Wheeler, D. Burnett, T. Yuan, X. Vilajosana and K. Pister. ‘QuickCal: Assisted Calibration for Crystal-Free Micro-Motes’. In: *IEEE internet of things journal* (Aug. 2020). DOI: 10.1109/JIOT.2020.3015725. URL: https://hal.inria.fr/hal-02916810.

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

[5] B. Kilberg, F. M. R. Campos, F. Maksimovic, T. Watteyne and K. S. J. Pister. ‘Accurate 3D Lighthouse Localization of a Low-Power Crystal-Free Single-Chip Mote’. In: *Journal of Microelectromechanical Systems* 29.5 (Aug. 2020). DOI: 10.1109/JMEMS.2020.3011460. URL: https://hal.inria.fr/hal-02916806.

[6] P. Muhlethaler, E. Renault and S. Boumerdassi. ‘Design and Evaluation of Flooding-Based Location Service in Vehicular Ad Hoc Networks’. In: *Sensors* 20.8 (Apr. 2020), p. 2389. DOI: 10.3390/s20082389. URL: https://hal.archives-ouvertes.fr/hal-02551318.

[7] Z. Zhang, S. D. Glaser, T. Watteyne and S. Malek. ‘Long-term Monitoring of the Sierra Nevada Snowpack Using Wireless Sensor Networks’. In: *IEEE internet of things journal* (June 2020). DOI: 10.1109/JIOT.2020.2970596. URL: https://hal.inria.fr/hal-01388391.

11.2 Publications of the year

International journals

[8] A. Abane, M. Daoui, S. Bouzefrane, S. Banerjee and P. Muhlethaler. ‘A Realistic Deployment of Named Data Networking in the Internet of Things’. In: *Journal of Cyber Security and Mobility* 9.1 (2020). DOI: 10.13052/jcsm2245-1439.911. URL: https://hal.archives-ouvertes.fr/hal-02920555.

[9] S. Baccari, M. Hadded, H. Touati and P. Muhlethaler. 'A secure trust-aware cross-layer routing protocol for Vehicular Ad hoc Networks'. In: *Journal of Cyber Security and Mobility* (2020). URL: https://hal.archives-ouvertes.fr/hal-03027480.

[10] G. Boquet, P. Tuset-Peiró, F. Adelantado, T. Watteyne and X. Vilajosana. 'LoRa-E: Overview and Performance Analysis'. In: *IEEE Communications Magazine* (1st Dec. 2020). URL: https://hal.inria.fr/hal-03115551.

[11] F. Boukhalfa, M. Hadded, P. Muhlethaler and O. Shagdar. 'Performance Evaluation of an Active Signaling based Time-Slot Scheduling Scheme for connected vehicles'. In: *Annals of Telecommunications - annales des télécommunications* (2020). URL: https://hal.archives-ouvertes.fr/hal-02981063.

[12] T. Chang, M. Vučinić, X. Vilajosana Guillén, D. Dujovne and T. Watteyne. '6TiSCH Minimal Scheduling Function: Performance Evaluation'. In: *Internet Technology Letters* (2020). DOI: 10.1002/itl2.170. URL: https://hal.inria.fr/hal-02616274.

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