UMR IRISA

Activity Report 2025

Team E4SE

Enabling Affordable Smarter Environment

Joint team with Centre Inria de l'Université de Rennes

D2 – Networks, Telecommunications and Services

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1 Team composition

Researchers and faculty

Jean-Marie Bonnin, Professor, IMT Atlantique, head of the team
Paul Couderc, Researcher, Inria
Tayeb Lemlouma (since Jan 2025), Associate Professor, Univ. Rennes
Bruno Stevant (since Jan 2025), Associate Professor, IMT Atlantique
Frédéric Weis, Professor, Univ. Rennes

Research engineers, technical staff

Abdoul-Majid Garba-Zibo (until Nov 2025), IMT Atlantique

PhD students

Antoine Le Borgne (until November 2025), Orange Labs Lannion (CIFRE), Matisse
Maxime Cancouet, Canon CRF (CIFRE), SPIN
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Mariam Issa, Univ. Rennes, Matisse
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2 Preliminary Remarks

After a challenging start, the E4SE team has now reached a steady and productive pace, with all permanent members actively engaged in one or more ongoing research projects. Our main concern is no longer initiating projects but rather limiting the number of engagements, as the difficulty of recruiting researchers and engineers has become a significant time-consuming challenge for the team.

In parallel, all permanent team members are now involved in PhD supervision, with an average of six PhD students-which was initially set as the team's maximum target. We have developed our collaboration with Alain-Jérôme Fougères (ECAM Rennes), particularly on multi-agent systems and software engineering. This collaboration has already led to a highly productive PhD project with Juliette Grosset. This year, we welcome Bruno Stévant (IMT Atlantique) to the team to strengthen our expertise in Edge Computing and reinforce the connection between networking and software engineering. We also include Tayeb Lemlouma (Univ. Rennes) who will bring his expertise in IoT and IA applied in the eHealth domain.

2.1 Future development

Looking ahead, we aim to expand the eHealth dimension within the team, with a clear strategy to be outlined in our upcoming team project proposal in the coming months. Since the inception of E4SE, we have identified that our approach-leveraging ephemeral local interactions for service implementation-is particularly well-suited to healthcare environments. This methodology complements centralized approaches while mitigating several key challenges, such as:

- Reducing dependence on centralized infrastructure, which is critical in hospitals where failures or cyberattacks (e.g., ransomware) can severely impact operations.
- Enhancing privacy protection, an essential aspect in medical environments.
- Facilitating interoperability and market openness, enabling better management of the diversity and heterogeneity of actors involved in healthcare service deployment.

To strengthen this new research direction, we are initiating a tight collaboration with Mounir Mokthari (Professor, IMT) with whom we elaborated two European project proposals. Additionally, we are also working with Bessam Abdulrazak (Professor, Université de Sherbrooke) as an IMT Atlantique associate researcher to further develop expertise in this field.

In 2025, the E4SE team has finalized its new team project for the upcoming period. This project clarifies our scientific positioning around local interactions, cooperative systems, and their extension toward smart environments and eHealth applications.

We have initiated the validation process with the IRISA scientific direction. This work also helped us to consolidate our collaborations and to structure our research axes more clearly.

3 Overall objectives

3.1 Overview

The technologies necessary for the development of pervasive applications are now widely available and accessible for many uses: short/long-range and low energy communications, a broad variety of visible (smart objects) or invisible (sensors and actuators) objects, as well as the democratization of the Internet of Things (IoT). Large areas of our living spaces are now instrumented. The concept of Smart Spaces is about to emerge, based upon both massive and apposite interactions between individuals and their everyday working and living environments: residential housing, public buildings, transportation, etc. The possibilities of new applications are boundless. Many scenarios have been studied in laboratories for many years and, today, a real ability to adapt the environment to the behaviors and needs of users can be demonstrated. However mainstream pervasive applications are barely existent, at the notable exception of the ubiquitous GPS-based navigators. The opportunity of using vast amounts of data collected from the physical environments for several application domains is still largely untapped. The applications that interact with users and act according to their environment with a large autonomy are still very specialized.

They can only be used in the environment they had especially been developed for (for example "classical" home automation tasks: comfort, entertainment, surveillance). They are difficult to adapt to increasingly complex situations, even though the environments in which they evolve are more open, or change over time (new sensors added, failures, mobility etc.).

Developing applications and services that are ready to deploy and evolve in different environments should involve a significant cost reduction. Unfortunately, designing, testing and ensuring the maintenance as well as the evolution of a pervasive application remain very complex. In our view, the lack of resources by which properties of the real environment are made available to application developers is a major concern. Building a pervasive application involves implementing one or more logical control loops which include four stages (see figure 1-a): (1) data collection in the real environment, (2) the (re)construction of information that is meaningful for the application and (3) for decision making, and finally, (4) action within the environment. While many decision-algorithms have been proposed, the collection and construction of a reliable and relevant perception of the environment and, in return, action mechanisms within the environment still pose major challenges that the EASE project is prepared to deal with.

Most current solutions are based on a massive collection of raw data from the environment, stored on remote servers. Figure 1-a illustrates this type of approach. Exposure of raw sensor values to the decision-making process does not allow to build relevant contexts that a pervasive application actually needs in order to shrewdly act/react to changes in the environment. So, the following is left up to the developer:

- To characterize more finely raw data beyond its simple value, for example, the acquisition date,the nature of network links crossed to access the sensor, the durability and accuracy of value reading, etc.
- To exploit this raw data to calculate a relevant abstraction for the application,

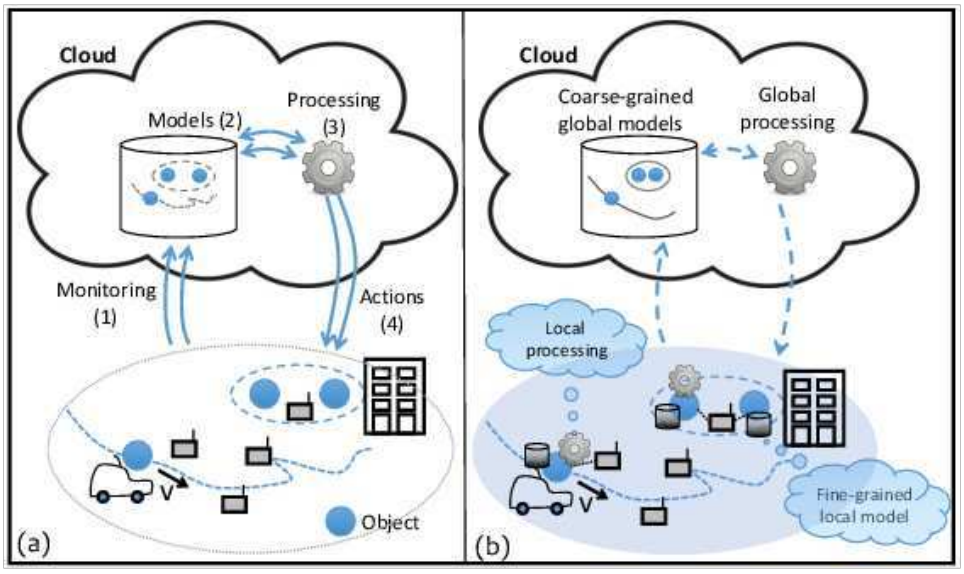


Figure 1: Adaptation processes in pervasive environments

such as, whether the room is occupied, or whether two objects are in the same physical vicinity.

- To modify the environment when possible.

Traditional software architectures isolate the developer from the real environment that he has to depict according to complex, heavy and expensive processes. However, objects and infrastructure integrated into user environments could provide a more suitable support to pervasive applications: description of the actual system's state can be richer, more accurate, and, simultaneously, easier to handle; the applications' structure can be distributed by being built directly into the environment, facilitating scalability and resilience by the processing autonomy; finally, moving processing closer to the edge of the network avoids major problems of data sovereignty and privacy encountered in infrastructures very dependent on the cloud. We strongly believe in the advantages of specific approaches to the fields of edge computing and fog computing, which will reveal themselves with the development of Smart Spaces and an expansive growth of the number of connected objects. Indeed, ensuring the availability and reliability of systems that remain frugal in terms of resources will become in the end a major challenge to be faced in order to allow proximity between processing and end-users. Figure 1 displays the principle of "using data at the best place for processing". Fine decisions can be made closer to the objects producing and acting on the data, local data characterization and local processing de-emphasize the computing and storage resources of the cloud (which can be used for example to store selected/transformed data for global historical analysis or optimization).

EASE aims at developing a comprehensive set of new interaction models and system architectures to considerably help pervasive application designers in the development phase with the side effect to ease the life cycle management. We follow two main

principles:

- Leveraging local properties and direct interactions between objects, we would be able to enrich and to locally manage data produced in the environment. The application would then be able to build their knowledge about their environment (perception) in order to adjust their behavior (e.g. level of automation) to the actual situation.
- Pervasive applications should be able to describe requirements they have on the quality of their environmental perception. We would be able to achieve the minimum quality level adapting the diversity of the sources (data fusion/aggregation), the network mechanisms used to collect the data (network/link level) and the production of the raw data (sensors).

3.2 Scientific foundations

3.2.1 Collecting pertinent information

In our model, applications adapt their behavior (for instance, the level of automation) to the quality of their perception of the environment. This is important to alleviate the development constraint we usually have on automated systems. We "just" have to be sure a given process will always operate at the right automation level given the precision, the completeness or the confidence it has on its own perception. For instance, a car passing through a crossing would choose its speed depending on the confidence it has gained during perception data gathering. When it has not enough information or when it could not trust it, it should reduce the automation level, therefore the speed, to only rely on its own sensors. Such an adaptation capability shift the requirements from the design and deployment (availability, robustness, accuracy, etc.) to the **assessment of the environment perception** which we aim to facilitate in this first research axis.

Data characterization. The quality (freshness, accuracy, confidence, reliability, confidentiality, etc.) of the data are of crucial importance to assess the quality of the perception and therefore to ensure proper behavior. The way data is produced, consolidated, and aggregated while flowing to the consumer has an impact on its quality. Moreover, part of these quality attributes requires to gather information at several communication layers from various entities. For this purpose, we want to design **lightweight cross-layer interactions** to collect relevant data. As a "frugality" principle should guide our approach, it is not appropriate to build all the attributes we can imagine. It is therefore necessary to identify attributes relevant to the application and to have mechanisms to activate/deactivate at run-time the process to collect them.

Data fusion. Raw data should be directly used only to determine low-level abstraction. Further help in abstracting from low-level details can be provided by **data fusion** mechanisms. A good (re)construction of meaningful information for the application reduces the complexity of the pervasive applications and helps the developers to concentrate on the application logic rather than on the management of raw data. Moreover, the reactivity required in pervasive systems and the aggregation of large amounts of data (and its processing) are antagonists. We study **software services that can be deployed closer to the edge of the network**. The exploration of data fusion

techniques will be guided by different criteria: relevance of abstractions produced for pervasive applications, anonymization of exploited raw data, processing time, etc.

Assessing the correctness of the behavior. To ease the design of new applications and to align the development of new products with the ever faster standard developments, continuous integration could be used in parallel with continuous conformance and interoperability testing. We already participate in the design of new shared platforms that aim at facilitating this by providing remote testing tools. Unfortunately, it is not possible to be sure that all potential peers in the surrounding have a conforming behavior. Moreover, upon failure or security breach, a piece of equipment could stop operating properly and lead to global mis-behavior. We want to propose conceptual tools for **testing devices at runtime in the environment**. The result of such conformance or interoperability tests could be stored safely in the environment by an authoritative testing entity. Then the application could interact with the device with higher confidence. The confidence level of a device could be part of the quality attribute of the information it contributed to generate. The same set of tools could be used to identify misbehaving device for maintenance purposes or to trigger further testing.

3.2.2 Building relevant abstraction for new interactions

The pervasive applications are often designed in an ad hoc manner depending on the targeted application area. Ressources (sensors / actuators, connected objets, etc.) are often used in silos which complexifies the implementation of rich pervasive computing scenarios. In the second research axis, we want to get away from technical aspects to identify **common and reusable system mechanisms** that could be used in various applications.

Tagging the environment. Information relative to the environment could be stored by the application itself, but it could be complex to manage for mobile applications since it could cross a large number of places with various features. Moreover the developer has to build his own representation of information especially when he wants to share information with other instances of the same application or with other applications. A promising approach is to store and to maintain this information associated to an object or to a place, in the environment itself. The infrastructure should provide services to application developers: add/retrieve information in the environment, share information and control who can access it, add computed properties to object for further usage. We want to study an **extensible model to describe and augment the environment**. Beyond a simple distributed storage, we have in mind a new kind of interaction between pervasive applications and the changing environment and between applications themselves.

Taking advantages of the spatial relationships. To understand the world they have to interact with, pervasive applications often have to (re)build a model of it from the exchange they have with others or from their own observations. A part of the programmer's task consists in building a model of the spatial layout of the objects in the surrounding. The term layout can be understood in several ways: the co-location of multiple objects in the same vicinity, the physical arrangement of two objects relative to each other, or even the crossing of an object of a physical area to another, etc. Remotely determining these spatial properties (see figure 1-a) is difficult without exchanging a lot

of information. Properties related to the spatial layout are far easier to characterize locally. They could be abstracted from the interaction pattern without any complex virtual representation of the environment (see figure 1-b). We want to be able to rely on this type of spatial layout in a pervasive environment. In the prior years, the members of EASE already worked on **models for processing object interactions** in the physical world to automatically trigger processing. This was the case in particular of the spatial programming principle: physical space is treated as a tuple-space in which objects are automatically synchronized according to their spatial arrangement. We want to follow this approach by considering **richer and more expressive programming models**.

3.2.3 Acting on the environment

The conceptual tools we aim to study must be frugal: they use as few resources as possible, while having the possibility to use much more when it is required. Data needed by an application is not made available for "free"; for example, it costs energy to measure a characteristic of the environment, or to transmit it. So this "design frugality" requires **a fine-grained control** on how data is actually collected from the environment. The third research axis aims at designing solutions that give this control to application developers by acting on the environment.

Acting on the data collection. We want to be able to identify what information are really needed during the perception elaboration process. If a piece of data is missing to build a given information with the appropriate quality level, the data collection mechanism should find relevant information in the environment or modify the way it aggregates it. These could lead to a modification of the behavior of the network layer and the path the piece of data uses in the aggregation process.

Acting on object interactions. Objects in the environment could adapt their behavior in a way that strongly depends on the object itself and that is difficult to generalize. Beyond the specific behaviors of actuators triggered through specialized or standard interfaces, the production of information required by an application could necessitate an adaptation at the object level (eg. calibration, sampling). The environment should then be able to initiate such an adaption transparently to the application, which may not know all objects it passes by.

Adapting object behaviors. The radio communication layers become more flexible and able to adapt the way they use energy to what is really required for a given transmission. We already study how beamforming techniques could be used to adapt the multicast strategy for video services. We want to show how playing with these new parameters of transmissions (e.g. beamforming, power, ...) allows to control spatial relationships objects could have. There is a tradeoff to find between the capacity of the medium, the electromagnetic pollution and the reactivity of the environment. We plan to extend our previous work on interface selection and more generally on what we call **opportunistic networking**.

3.3 Application domains

3.3.1 Automation in Smart Cities

The domain of Smart Cities is still young but it is already a huge market which attracts number of companies and researchers. It is also multi-fold as the words "smart city" gather multiple meanings. Among them one of the main responsibilities of a city, is to organize the transportation of goods and people. In intelligent transportation systems (ITS), ICT technologies have been involved to improve planification and more generally efficiency of journeys within the city. We are interested in the next step where efficiency would be improved locally relying on local interactions between vehicles, infrastructure and people (smartphones).

For the future autonomous vehicle are now in the spotlight, since a lot of works has been done in recent years in automotive industry as well as in academic research centers. Such unmanned vehicles could strongly impact the organisation of the transportation in our cities. However, due to the lack of a definition of what is an "autonomous" vehicle, it is still difficult to see how these vehicles will interact with their environment (eg. road, smart city, houses, grid, etc.). From augmented perception to fully cooperative automated vehicle, the autonomy covers various realities in terms of interaction the vehicle relies on. The extended perception relies on communication between the vehicle and surrounding roadside equipments. That helps the driving system to build and maintain an accurate view of the environment. But at this first stage the vehicle only uses its own perception to make its decisions. At a second stage, it will take advantages of local interaction with other vehicles through car-to-car communications to elaborate a better view of its environment. Such "cooperative autonomy" does not try to reproduce the human behavior anymore, it strongly relies on communication between vehicles and/or with the infrastructure to make decision and to acquire information on the environment. Part of the decision could be centralized (almost everything for an automatic metro) or coordinated by a roadside component. The decision making could even be fully distributed but this puts high constraints on the communications. Automated vehicles are just an example of smart city automated processes that will have to share information within the surrounding to make their decisions.

3.3.2 Pervasive applications in uncontrolled environnements

Some limitations of existing RFID technology become challenging: unlike standard RFID application scenarios, pervasive computing often involves uncontrolled environment for RFID, where tags and reader have to operate in much more difficult situations that those usually encountered or expected for classical RFID systems.

RFID technology is to avoid missing tags when reading multiple objects, as reading reliability is affected by various effects such as shadowing or wave power absorption by some materials. The usual applications of RFID operate in a controlled environment in order to reduce the risk of missing tags while scanning objects. In pervasive computing applications, a controlled reading environment is extremely difficult to achieve, as one of the principles is to enhance existing processes "in situ", unlike the controlled conditions that can be found in industrial processes. Consider for example a logistic application,

where RFID tags could be used on items inside a package in order to check for its integrity along the shipping process. Tags would likely be placed randomly on items inside the package, and reading conditions would be variable depending on where the package is checked.

RFID operation in uncontrolled environments is challenging because RFID performance is affected by multiple parameters, in particular:

- Objects materials (to which tags are attached to),
- Materials in the surrounding environment,
- RFID frequency spectrum,
- Antenna nature and placement with respect to the tags.

In controlled environment, the difficulty to read tags can be limited by using the appropriate parameters to maximize the RFID performance for the application. But in many cases, it is needed to read large number of objects of various nature, arranged randomly in a given area or container. **Most pervasive computing applications fall in this context**.

3.3.3 Data collection for precision agriculture

The use of sensor networks can be useful to support environmentally friendly production in the agricultural sector: monitoring of plant cover, plant disease detection, fine-grained plant treatments. Nevertheless, the digital tools used for this type of deployment were not designed to be broadly usable by non-specialists and have not yet established themselves among the agricultural community.

In addition, in agriculture as in many fields, the use of digital technology has mostly been carried out under the paradigm of massive data collection: logging as much information as possible, storing the data and then implementing statistical and IT methods to extract meaningful information. This approach raises problems of energy storage and consumption, increasing the environmental footprint of digital technology and limiting deployments of operational and sustainable systems.

Very small connected objects are now able to execute software codes, to drive many sensors, to send data pair with other devices in their neighborhood and to pre-process data for cleaning/aggregation. Our ambition is to optimize the crop monitoring system from a data and energy perspectives, using generic software mechanisms as close as possible to the sensor node and introducing "intelligence" into the data collection mechanisms.

Our approach is based on the quality of the data produced by the sensor nodes distributed in the environment. Data quality can be broken down into different dimensions: precision, confidence, durability, etc. Characterizing data quality requires the developer of an application to analyze and possibly control how this data is produced and collected. Usually, this task is performed on an ad hoc basis, with a strong dependence on the objectives of the data collection and not very reproducible as the environment in

which the sensors are deployed evolves. The challenge is to offer mechanisms that will adapt, without additional software developments, to the many field experiments carried out for precision agriculture.

3.3.4 Connected Drone Systems and Fair Multi-Agent Network Intelligence

The emergence of connected drone systems operating over cellular networks raises new challenges for future communication infrastructures, particularly in the context of 6G networks. These systems must integrate aerial mobility into existing radio access networks (RAN) while ensuring efficient use of limited resources and maintaining a high Quality of Experience (QoE) for both aerial and terrestrial users. In this perspective, modeling and evaluating the impact of drone trajectories on network performance becomes essential, especially when considering multi-operator environments and the interaction with existing infrastructures and constraints. At the same time, the increasing complexity of network environments calls for more advanced decision-making mechanisms, where multiple stakeholders, such as operators, users, and autonomous systems must coordinate under potentially conflicting objectives. Traditional approaches based on centralized optimization or purely individual decision- making are no longer sufficient to address these challenges. Instead, there is a need for distributed and adaptive solutions capable of jointly optimizing communication, computation, and resource allocation in dynamic environments.

In this context, connected drones can be seen as intelligent agents embedded in a larger multi-agent system, where decisions such as trajectory planning, communication strategies, or computation offloading must account not only for local constraints (e.g., latency, energy, connectivity) but also for global network conditions. For instance, adaptive architectures combining onboard intelligence and edge/cloud resources can improve system performance, while empirical models of cellular connectivity enable anticipatory decision-making based on predicted network quality along drone trajectories. Beyond performance optimization, an important challenge lies in ensuring fairness in resource allocation and decision-making processes. In multi-agent environments, agents may have competing objectives, and maximizing overall efficiency does not necessarily lead to equitable outcomes. Recent advances in multi-agent reinforcement learning (MARL) address this limitation by introducing cooperative and altruistic behaviors, allowing agents to balance individual rewards with collective objectives. Such approaches enable a more equitable distribution of resources while preserving high system performance.

By combining adaptive drone-network integration with fair and cooperative multi-agent intelligence, this application domain contributes to the design of future autonomous systems capable of efficiently sharing network resources, coordinating their actions, and adapting to complex and evolving environments. It provides a promising foundation for scalable, resilient, and sustainable networked systems in emerging aerial and multi-stakeholder scenarios. Such cooperative multi-agent intelligence can also be beneficial in other application domains, such as smart spaces. In these environments, it can support advanced e-health services, including the automatic assessment of elderly people's level of dependency, as well as the promotion of overall well-being and quality of life.

4 Scientific achievements

4.1 Cooperative ITS & automated vehicles

Participants: Jean-Marie Bonnin, Bruno Stévant, Frédéric Weis, Maxime Cancouet, Manoj Gudi, Hadi Houssainy.

4.1.1 Increasing the autonomy of AIVs integrated into a fleet using collective intelligence strategies

In 2024, Juliette Grosset made significant contributions to the collective intelligence strategies for autonomous industrial vehicles (AIVs), focusing on enhancing fleet coordination, task allocation, cooperative perception, and energy management. Her work addressed the challenges of integrating AIVs into dynamic and industrial environments, where efficient and autonomous decision-making is crucial. A key outcome of her research was the development of collective decision-making frameworks that leverage multi-agent systems and V2X communications to improve operational efficiency. Juliette Grosset received the 2025 PhD Award from the SPIN Doctoral School, recognizing both the scientific quality and industrial impact of her work on collective intelligence strategies for autonomous industrial vehicles.

In 2025, we continued the development and dissemination of the research initiated in the PhD work of Juliette Grosset, focusing on cooperative perception and coordination mechanisms for autonomous vehicle systems. These contributions have been further consolidated through ongoing publications and extensions of the proposed models [3, 2]. This work has also led to the initiation of a new collaboration with Udayana University, opening new perspectives for extending our research on cooperative systems in an international context [4].

Juliette Grosset's work contributed to the launch of the Alpha project, which was completed this year. IMT Atlantique contributed to the Alpha project by investigating cooperative mechanisms to improve both performance and safety in autonomous vehicle fleets operating in constrained logistic environments. The work focused on the design and evaluation of distributed coordination strategies relying on V2X communications, without requiring centralized control. On the performance side, we developed and validated a lightweight platooning approach without predefined leader, combined with dynamic merging strategies at intersections. These mechanisms were evaluated using SUMO and OMNeT++ co-simulation, demonstrating improved traffic fluidity, reduced congestion, and better inter-vehicle spacing stability under high-density conditions. On the safety side, we designed a cooperative perception architecture based on infrastructure sensors and V2X communication. Using CARLA, ROS2, and OpenCDA, we implemented the generation and dissemination of Cooperative Perception Messages (CPMs) to detect pedestrians beyond line-of-sight. The results showed that vehicles could anticipate hazards and react appropriately, even in occluded scenarios. These contributions were supported by the development of a complete simulation toolchain, including a digital twin of the Alpha circuit and a custom AGV model. The outcomes were validated through realistic scenarios. Overall, IMT Atlantique demonstrated the

relevance of cooperative, infrastructure-assisted approaches to enhance both efficiency and safety in industrial autonomous mobility systems.

4.1.2 Cooperative Perception Infrastructure

As part of his CIFRE agreement with Canon Research Centre France (Canon CRF) and IMT Atlantique, we continued his work in 2025 on the monitoring of cooperative perception infrastructures, contributing both to his PhD research and to related European projects.

An initial contribution consisted in preparing complementary experiments with the Commissariat à l'énergie atomique et aux énergies alternatives (CEA) prior to the final real-world demonstration of the SELFY project, which took place in April 2025. In particular, this work enabled the validation of the behavior of the monitoring tools developed within the SELFY project.

These experiments also highlighted systematic errors in the behavior of the CRF video content analytics (VCA) software, resulting in inaccuracies in both the estimated object positions and their associated confidence metrics. This behavior was further confirmed through additional experiments conducted within the ROADVIEW project.

This work led to the development of a method based on a specifically instrumented vehicle to measure positioning deviations, correct infrastructure-based position estimates, and accurately model the uncertainty associated with detected objects. This contribution was first valorized through a patent filed in July 2025 [13].

Subsequently, this method was evaluated using data collected within the ROADVIEW project, notably leveraging access to a camera infrastructure deployed in Finland. In particular, high-precision vehicular data provided by the Finnish Geospatial Research Institute (FGI) were used to validate the correction method under various environmental conditions, including snowy conditions and nighttime scenarios.

This work resulted in a conference paper co-authored with FGI, which was submitted and accepted to the IEEE Intelligent Vehicles Symposium (IV) 2026 [5].

Another research direction focused on methods for broadcasting real-time information regarding the operational status and perception capabilities of roadside units (RSUs), which also resulted in a patent filing [14].

4.2 Hybridization of 5G-V2X with other communication technologies in the context of cooperative Intelligent Transport Systems

The first year of this work focused on establishing the state of the art through a systematic literature review in order to identify research gaps. A major challenge addressed was improving interoperability across the V2X communication stack while also identifying opportunities to enhance performance in heterogeneous networking environments.

This research, conducted as part of the PEPR Réseaux du Futur (FITNESS) program, required the candidate to develop a thorough understanding of competing V2X technologies that are nevertheless expected to be deployed simultaneously. For instance, in Europe, both 5G-V2X and DSRC are encouraged to be developed and deployed in

coexistence within the 5.9 GHz band by dividing the available channels. Although coexistence solutions for 5G-V2X and DSRC exist, they are often not readily deployable at scale. Of the 30 MHz bandwidth available for ITS, 10 MHz is reserved for DSRC-based vehicles. The objective of this work was therefore to determine whether these vehicles could congest the network with periodic messages primarily carrying telemetry data, known as Cooperative Awareness Messages (CAMs). Based on this analysis, the candidate formulated the problem and proposed reducing CAM size using Static Context Header Compression (SCHC). This contribution was accepted at the IEEE WCNC conference [7].

CAM messages are standardized by the European Telecommunications Standards Institute (ETSI) and specified using Abstract Syntax Notation One (ASN.1). However, not all V2X devices natively support ASN.1-based models. For example, edge network devices such as roadside units (RSUs) are frequently configured using data models defined in YANG, standardized by the Internet Engineering Task Force (IETF). Developing a translation mechanism from ASN.1 to YANG for CAM messages would enable these messages to be encoded in faster-to-process formats such as CoRECONF/CBOR. This format is also more interoperable with network devices and can support more efficient management of Internet-enabled vehicles (IoVs). This work involved identifying gaps in the literature, defining ASN.1-to-YANG translation rules, and evaluating the performance of CAM messages encoded in CoRECONF/CBOR through benchmarking on an onboard unit (YoGoKo platform). This contribution was accepted at the IEEE/IFIP NOMS 2026 conference [8].

In the current year, the research focuses on developing mechanisms to repurpose autonomous vehicles equipped with dual-band OBUs and on investigating pedestrian safety in heterogeneous networks. The work will also extend the YANG-to-ASN.1 translation approach by defining formal semantics and developing proofs to support source-to-source transpilers.

4.2.1 Resource allocation strategies for CCAM systems operating over 5G networks

This research focuses on proactive and intelligent resource allocation strategies for CCAM systems operating over 5G networks. The main objective is to develop mechanisms capable of anticipating the dynamic and stringent Quality of Service (QoS) requirements of vehicular applications, including safety-critical and cooperative driving use cases, and provisioning radio and computing resources proactively rather than reactively.

This work lies at the intersection of 5G New Radio (NR) sidelink communications (C-V2X / PC5 interface), network slicing, and Multi-access Edge Computing (MEC).

This work is conducted within the framework of the PIEEC funding project, which provides both the research context and financial support. The thesis is carried out at IMT Atlantique and aims to produce contributions bridging theoretical resource allocation frameworks with practical CCAM deployment scenarios.

This year was dedicated to an in-depth literature review and to the acquisition of fundamental expertise in 5G RAN and Core architectures, radio resource allocation

mechanisms, and compute resource management in MEC environments. A comprehensive state-of-the-art report was produced and submitted within the PIEEC project, providing the bibliographic foundation upon which the forthcoming research contributions will build.

The work is now transitioning toward the problem formulation phase. Building on the literature review, the current focus is on identifying the key scientific gaps that will form the basis of the first research contribution. In particular, the research investigates the limitations of reactive resource allocation strategies in highly dynamic V2X environments and explores how proactive, prediction-based approaches may address these limitations while satisfying strict URLLC service-level requirements.

4.3 Monitoring of in-field risk of infection events using smart IoT nodes

Participants: Jean-Marie Bonnin, Hassan Hammoud, Frédéric Weis.

This year we studied the impact of local data storage and memory operations on the overall energy footprint of resource-constrained IoT nodes. While much of the existing literature focuses primarily on communication or sensing costs, this work highlights that memory accesses and data management strategies can also significantly influence the operational lifetime of autonomous IoT systems.

The main contribution of this work is the design and evaluation of an energy-aware local data management mechanism that reduces unnecessary storage operations by introducing adaptive data summarization strategies. Instead of systematically storing raw sensor data, the proposed approach relies on the generation of compact representations of relevant events, allowing the system to preserve essential information while limiting memory usage and the associated energy costs. This contribution demonstrates how software-level data management policies can play a central role in the design of sustainable extreme-edge computing systems.

The work also provides a structured analysis of the trade-offs between data accuracy, memory usage, and energy consumption by comparing alternative summarization strategies. One strategy favors analytical precision by maintaining event-level summaries, while another prioritizes energy efficiency by progressively aggregating information into more compact representations. This analysis provides methodological insights into how data management policies can be tuned depending on application constraints, particularly in long-term environmental monitoring scenarios where system lifetime is a critical factor.

From a methodological perspective, this contribution is grounded in an experimental approach, as the evaluation relies on simulations derived from empirical power measurements obtained from the experimental IoT platform developed during the thesis. This strengthens the validity of the results and positions the work beyond purely theoretical optimization approaches by linking software mechanisms with measured hardware behavior. The results show that appropriate data management strategies can significantly reduce energy consumption and therefore extend node lifetime, confirming that intelligent data handling is a key design dimension for extreme-edge IoT architectures.

Beyond the immediate results, this work also opens several research perspectives related to distributed data management at the edge, including opportunities for collaborative data sharing between nodes, redundancy reduction strategies, and adaptive sensing coordination. These directions highlight the importance of moving toward more autonomous and cooperative IoT infrastructures capable of dynamically adapting their data management strategies according to resource constraints and application needs.

4.4 Mediation Infrastructure for Ephemeral Interactions in Smart Environments

Participants: Paul Couderc, Mariam Issa, Jean-Marie Bonnin.

The period between January 2025 and January 2026 constituted the core implementation phase of this work, during which the candidate built upon the investigated advertisement-based communication paradigm to enable practical application-level data exchange. This work systematically addressed the research gaps identified in the previously established state of the art. Prior to January 2025, the work established its foundations through an extensive literature review of advertisement-based communication across diverse application domains. A key finding was that numerous domains already make use of this technique without providing a formal definition of the paradigm itself. This work therefore formalized the paradigm by defining its requirements and conditions based on three key dimensions: topology, performance, and deployment constraints. A systematic evaluation of 11 widely used wireless technologies was then conducted to assess their suitability for association-less communication. This analysis identified Wi-Fi and BLE as the two most suitable enabling technologies. However, it was also observed that advertisements alone do not constitute a complete communication system. In environments characterized by massive broadcast traffic, efficient data handling and content-based filtering mechanisms become essential. Based on this analysis, three major research directions were identified and guided the work conducted after January 2025:

- The need for content-based filtering techniques for advertisement streams
- The need for seamless data exchange across heterogeneous technologies (BLE and Wi-Fi)
- The need for middleware solutions to abstract implementation complexity for application developers

This state-of-the-art study resulted in a survey article entitled "Wi-Fi and BLE Advertisement-Based Communication for Ephemeral Interactions: A Survey", which was accepted in February 2026 for publication in the Peer-to-Peer Networking and Applications journal (Springer).

The work was then extended to support seamless application data exchange between Wi-Fi-based and BLE-based advertisement mechanisms. A dual-radio system was implemented and evaluated on ESP32 hardware in order to measure the trade-offs induced by technology coexistence in terms of payload capacity, scheduling coordination,

and power consumption. This work was published at EAI INTSYS 2025 [10]. Finally, the work proposed *Éphémère*, a middleware system motivated by the observation that implementing advertisement-based communication systems introduces significant technical complexity for application developers. There is therefore a strong need to abstract low-level data transmission and processing mechanisms while providing a simple and clean API allowing developers to focus on application logic rather than communication mechanisms. Within *Éphémère*, a four-function API was designed to provide full abstraction:

define_schema() - declares custom data structures (e.g., ”name”, ”level”, ”age”)

publish() - broadcasts data using the defined schema

subscribe() - registers event-driven callbacks based on matching criteria

retrieve() - performs one-time queries on currently available data

The middleware automatically encodes developer-defined schemas into TLV format, computes hash values for integrity verification, and broadcasts the data over BLE advertisements (or Wi-Fi beacons, or both). On the receiver side, an event-driven framework was implemented to enable efficient content-based filtering through local processing. For example, a developer may subscribe to criteria such as *level = intermediate*, while the middleware transparently handles packet parsing, hash verification, schema decoding, and event matching. The measured performance characteristics demonstrate:

- A detection rate above 90% on host platforms (laptops and smartphones)
- A baseline publish-to-receive latency of approximately 50 ms
- Reduced code complexity, with approximately 6 lines of application code compared to more than 15 lines in comparable systems

However, a critical platform limitation was also identified: deployment on embedded ESP32 platforms achieves only a 60% detection rate. This limitation prevents the use of such platforms for safety-critical applications such as pedestrian-to-vehicle (V2P) collision warning. This result has important implications for deployment architecture decisions. A comparative analysis with existing middleware solutions further shows that *Éphémère* provides a particularly lightweight implementation stack. The system relies exclusively on schema-based broadcasting and local event filtering, without requiring routing protocols, mesh formation, distributed hash tables, publish/subscribe brokers, or overlay coordination mechanisms. The corresponding article is complete and will soon be submitted to a major international conference in the fields of pervasive computing or middleware. Overall, these contributions demonstrate that ephemeral interactions can benefit from communication paradigms specifically designed for their characteristics. This thesis shows that such paradigms can be systematically designed across the full communication stack, from the data transmission layer to the middleware abstraction layer and up to the application layer.

4.5 Optimization of UHF RFID Reading in Dense Environments

Participants: Paul Couderc, Jean-Marie Bonnin.

While previous work has focused on enhancing the MAC layer to reduce collisions through adaptive Q algorithms, the proposed approach instead optimizes power and environmental parameters at the physical (radio) layer. The underlying hypothesis is that dynamically adjusting multiple antennas and controlling transmission power at different levels can significantly improve tag identification performance in static or quasi-static dense tag environments.

This dynamic adaptation improves the system's ability to handle dense tag deployments and varying tag orientations. By jointly adjusting transmission power, the Q parameter, and environmental diversity through antenna switching, the proposed approach improves system efficiency without modifying the EPC Gen2 protocol, thereby preserving compatibility and scalability in dense multi-reader environments such as retail stores and warehouses.

A novel radio-layer strategy was therefore designed to optimize UHF RFID reading performance through coordinated adjustment of transmission power, Q values, and antenna switching, with the objective of achieving high reading rates while minimizing interference. This method provides an effective approach to mitigating collisions and improving energy efficiency in high tag-density environments, particularly when multiple readers operate in close proximity.

However, a well-known limitation of the Q protocol lies in the selection of the initial Q value, which is often suboptimal since the tag population, or an accurate estimate of it, is typically unknown a priori. This limitation may result in degraded performance during the initial reading phase. The proposed approach addresses this issue through dynamic adaptation of the Q parameter based on real-time observations, allowing performance to progressively improve as the system converges toward optimal operating conditions.

Experimental validation conducted using a programmable RFID platform demonstrated significant improvements in both reading efficiency and energy consumption, highlighting the practical relevance of this approach for real-world deployments. These results were published in [6].

4.6 Cooperative AI for the development of future sustainable networks

Participants: Franck Xu, Tayeb Lemlouma, Jean-Marie Bonnin.

In 2025, we conducted an in-depth study of the state of the art in multi-agent reinforcement learning (MARL), with a particular focus on mechanisms promoting fairness between agents in mixed-motive environments. This analysis highlighted a significant gap in the literature, where most approaches either focus on individual reward maximization or on global efficiency, with limited consideration for the distribution of rewards among agents. Building on this analysis, we proposed a novel MARL framework that

explicitly integrates altruistic behaviors and fair social welfare objectives. The proposed approach allows agents to balance their individual reward with a collective objective, taking into account both the total system performance and the equity of reward distribution. These contributions have been validated through a series of experiments in mixed-motive Markov games, demonstrating improved fairness properties while preserving competitive performance levels. This work led to the publication of the paper "Altruism and Fair Objective in Mixed-Motive Markov Games" at AAMAS 2026 [12].

This research constitutes the first step of the PhD work of Franck Xu and lays the foundation for future developments on cooperative and fair decision-making mechanisms in multi-agent systems, with potential applications in autonomous systems and resource-sharing environments.

4.7 Adaptive Architectures and Multi-Operator Connectivity for Connected Drones

Participants: Antoine Le Borgne, Tayeb LemLouma, Xavier Marjou (OLabs), and Fanny Parzysz (OLabs).

This work investigates the feasibility and evaluates the impact of using connected drones over operator cellular networks. To address this objective, we first analyzed existing approaches from the literature in related domains and identified the possible distribution of computation between onboard drone processing and distributed Cloud-based architectures. Early findings highlight that the diversity of use cases makes it difficult to converge toward a single unified architecture. Based on this observation, the study explores hybrid architectural solutions capable of dynamically adapting onboard processing and communication strategies according to network conditions. These conditions, which are specific to aerial mobility scenarios, differentiate this work from existing approaches. The goal is to improve the resilience, performance, and autonomy of drones by equipping them with enhanced decision-making capabilities.

Within this context, several complementary research directions were investigated. First, the orchestration of embedded artificial intelligence models for visual perception was studied by comparing chained architectures (i.e., successive specialized modules) with end-to-end composite models. Second, an empirical model of in-flight cellular connectivity was proposed, incorporating an onboard multi-operator score to predict network quality based on trajectory and environmental conditions. Finally, multiple inference scenarios (local, edge, and cloud) were evaluated, considering real-world use cases such as early fire detection, while accounting for latency, energy consumption, and robustness constraints.

The work led to several notable results. First, the comparison of embedded AI architectures for visual perception highlights trade-offs between accuracy, labeling cost, and model adaptability. Second, the dynamic modeling of cellular connectivity resulted in the design of a multi-operator scoring mechanism capable of anticipating Quality of Service and guiding computation offloading decisions. Third, experimental evaluation of inference strategies (local, edge, cloud) in realistic scenarios demonstrates the benefits of a hybrid and adaptive approach to maximize drone operational performance [11].

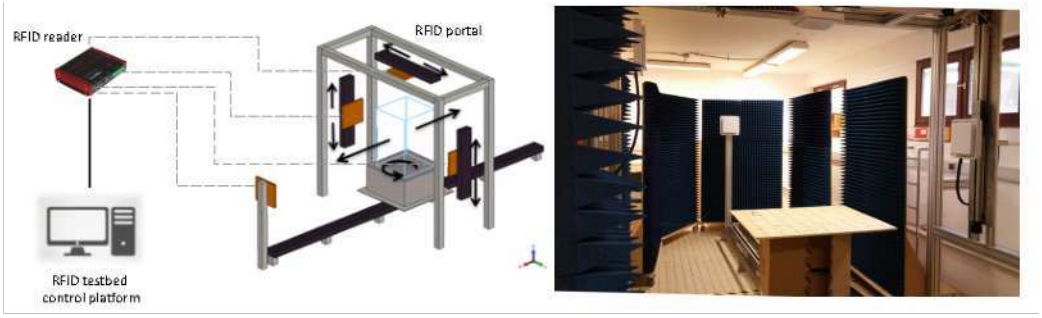


Figure 2: RFID Platform

5 Software development

5.1 Pervasive RFID

Participants: Paul Couderc, Hadi El-Hajj Chehade.

The RFID experiment testbed has been designed and deployed in collaboration with IETR (see Figure 2). This system allows both interactive testing as well as long running experiments of RFID reading protocols. It comprises a software platform allowing fine control over all the dynamic aspects influencing RFID readings: movements for target and antenna, RFID reader configuration, and smart antenna configuration (diversity and power control).

It is used and developped in the context of IsiCol project.

5.2 AgriSense

Participants: Hassan Hammoud, Frédéric Weis.

This platform is developed in the framework of a collaboration between EASE and the Demecology (Dynamics-Evolution-Modeling-Ecology) team of INRAe, which carries out work in plant epidemiology. The general objective is to develop precision monitoring solutions for their experimental vegetal plots.

The use of these very small objects (microcontrollers - MCU) for crop monitoring is promising. But it poses different problems, which we studied using this platform. Our hardware architecture is based on a very generic "on-the-shelf" MCU. The latter offers a fairly limited number of I/O interfaces: GPIO port, UART, etc. However, the environmental sensors used for crop monitoring have very variable features: digital or analog, using specialized communication protocols (e.g. SDI12), and can be particularly energy intensive (e.g. dielectric sensors measuring wetness). To address this issue, we designed an hardware architecture ensuring a stable link between the MCU and different types of sensors. This architecture is based on the design of a low-cost PCB, allowing to efficiently operate any type of sensors. This architecture is open (we are talking about an "open PCB"), very low cost, and can be easily adapted to different MCU architectures.

6 Contracts and collaborations

6.1 National Initiatives

6.1.1 Région Bretagne: IsiCol

Participants: *Hadi El-Hajj Chehade*, Paul Couderc, Jean-Marie Bonnin.

- Project type: Région Bretagne
- Dates: 2023–2025
- PI institution: Inria
- Other partners: Ekolis (lead), Samea-Innovation

In collaboration with Samea and Ekolis, the ISICOL project aimed to improve transport logistics through the use of RFID (Radio Frequency Identification) technology. RFID offers strong capabilities for identification, tracking, and data collection, but its integration into road transport logistics remains challenging due to dynamic environments and operational constraints.

ISICOL ("Integrated Solutions for Intelligent Control and Logistics") focused on the development of an autonomous RFID reader portal, enabling real-time monitoring and improved traceability of goods. The main objective was to design a battery-powered RFID solution with an intelligent reading protocol, capable of adapting to dynamic loading and unloading conditions while ensuring high reliability. The project relied on experimental validation using the INRIA-IETR PervasiveRFID platform, allowing controlled and reproducible evaluation scenarios.

Within the project, our work focused on the design of energy-efficient and robust RFID reading mechanisms, capable of maintaining high reading performance under challenging conditions such as high tag density or unfavorable propagation environments. We also contributed to the development and experimental validation of optimized reading algorithms, as well as to the integration of these mechanisms into industrial prototypes developed by the partners. These efforts led to a scientific publication presented at IEEE RFID-TA 2025 [6].

However, the project faced significant delays due to major recruitment difficulties. The research engineer initially selected could not be hired in time, and the final recruitment only became effective at the beginning of 2024. As a result, the effective contribution period was limited to approximately 12 months, which constrained the scope of the work.

Consequently, although the main technical objectives were partially achieved, several aspects-such as advanced antenna diversity exploitation, large-scale experimental validation, and full optimization of the reading system, could not be fully explored. Despite these limitations, the project enabled the validation of key concepts and strengthened our expertise in energy-constrained RFID systems for logistics applications.

6.1.2 Region Bretagne: Alpha

Participants: Jean-Marie Bonnin, *Juliette Grosset*, Abdoul-Majid Garba-Zibo.

- Project type: Region Bretagne
- Dates: 2023-2025
- PI institution: IMT Atlantique
- Other partners: Alstef (lead), ECAM, Secure-IC

This two-year project focused on transforming airport baggage transport through the deployment of Automated Guided Vehicle (AGV) fleets, as an alternative to traditional conveyor-based systems. BAGXONE, developed by Alstef Group, is an innovative AGV designed for automated baggage handling. Building on an initial deployment at Belgrade Airport, the Alpha project aimed to enhance this solution by integrating advanced technologies in performance optimization, cooperative control, safety, and cybersecurity.

IMT Atlantique (IRISA E4SE team) contributed to the project through the design and evaluation of cooperative mechanisms for AGV coordination, with a particular focus on distributed approaches relying on local interactions and V2X communications. The work addressed key challenges such as traffic fluidity, energy efficiency, and robustness in dense and constrained environments.

A detailed analysis of V2X constraints was conducted, comparing several communication technologies (ITS-G5, LTE-V2X, 5G-V2X, and Wi-Fi). Due to deployment and availability constraints, Wi-Fi-based solutions were identified as a practical and efficient alternative for industrial environments. Traffic simulations using SUMO enabled the identification of system bottlenecks and the proposal of optimizations, such as improved circuit design and regulation of pickup operations.

A lightweight platooning strategy without predefined leader, combined with dynamic merging policies at intersections, was developed and evaluated through co-simulation with OMNeT++ and Veins. These mechanisms demonstrated significant improvements in traffic stability, throughput, and energy efficiency, even under degraded communication conditions.

In parallel, a cooperative perception framework was implemented to improve pedestrian safety. Using Carla, ROS2, and OpenCDA, the system enabled the generation and dissemination of Cooperative Perception Messages (CPMs) based on infrastructure sensors. Simulations showed that AGVs could anticipate the presence of pedestrians in occluded scenarios and react accordingly.

The project officially started in mid-2023, but effective work began in early 2024 due to recruitment delays, which impacted the overall execution. As a result, some planned developments – particularly in large-scale validation and network integration – could not be fully completed.

Despite these limitations, the Alpha project successfully demonstrated the relevance of cooperative and distributed approaches for industrial autonomous mobility. It also led to a productive collaboration between academic and industrial partners. Building on these results, a new project focusing on robotic logistics in hospital environments is currently under preparation with part of the consortium.

6.1.3 PEPR 5G-FITNESS: PhD Hybridization of 5G-V2X with Other Communication Technologies in Cooperative ITS

Participants: Manoj Gudi, Frédéric Weis, Jean-Marie Bonnin.

This PhD thesis started in Dec 2024 is part of the PEPR 5G-FITNESS project, a French national research initiative addressing the challenges of 5G and future networks. The project aims to advance research and innovation in next-generation communication technologies, particularly in intelligent transportation systems (ITS). Given the uncertainties surrounding the deployment of V2X technologies, the project explores new hybrid communication architectures that leverage multiple technologies to enhance safety, efficiency, and interoperability in connected mobility.

The proposed PhD work focuses on hybridizing 5G-V2X with other communication technologies in the context of cooperative ITS. While ITS-G5 (based on WiFi) has been validated for basic safety applications, the emergence of 5G-V2X introduces opportunities and challenges in coexistence, interoperability, and optimal resource allocation. The research will investigate cross-layer mechanisms to facilitate communication between multiple V2X technologies, ensuring robust and efficient data exchange. The work will include simulation-based evaluations, development of decision mechanisms for selecting the most suitable communication interface, and potential contributions to standardization efforts (ETSI, ISO). The approach will first be tested in controlled industrial AGV environments before being extended to broader cooperative ITS scenarios.

6.1.4 PIEEC MECT Part: PhD Proactive Service-Based Resource Management for CCAM Applications

Participants: New PhD, Bruno Stévant, Jean-Marie Bonnin.

This PhD thesis is part of the PIEEC (Important Project of Common European Interest) ME/CT PART initiative, a large-scale European effort aimed at fostering innovation and sovereignty in key technological sectors. As part of this program, next-generation communication networks play a critical role in enabling Cooperative, Connected, and Automated Mobility (CCAM) applications. These applications require low-latency, high-reliability communication, making efficient resource allocation a crucial challenge. Ensuring fair, dynamic, and service-aware management of network resources is essential to supporting the growing demand for real-time cooperative mobility services.

The PhD research should start in 2025 and will focus on optimizing radio resource management for CCAM services. Traditional radio resource allocation mechanisms prioritize fairness and service-based classification, often leading to over-provisioning for high-demand applications. In the case of CCAM, a large number of critical services share limited spectrum resources, potentially causing network congestion. This work aims to develop a proactive, service-based resource allocation strategy that ensures communication meets strict time constraints while adopting a frugal approach. The research will explore centralized vs. decentralized allocation mechanisms, leveraging anticipatory resource distribution to prioritize safety-critical data. The proposed so-

lutions will be evaluated through simulations and experimental platforms, integrating real-world CCAM use cases.

6.2 Bilateral industry grants

6.2.1 PhD (CIFRE with Orange Labs): "Cooperative AI for Future Sustainable Networks"

Participants: Franck Xu, Tayeb LemLouma, Jean-Marie Bonnin.

This PhD thesis is part of Orange's Connectivity & Infrastructure Business (CIB) project, which aims to explore innovative solutions for the future of network infrastructures, particularly in the context of 6G networks. As networks become more complex and resource-intensive, ensuring their sustainability, efficiency, and resilience is a key challenge. In this context, multi-agent cooperation and artificial intelligence (AI) are emerging as crucial technologies to optimize network management while addressing economic, energy, and environmental constraints. The research builds on prior work in multi-agent reinforcement learning (MARL) and contributes to broader initiatives such as IRIS (Carbon 4) and Orange's Corporate Social Responsibility (CSR) programs.

The PhD focuses on developing Cooperative AI approaches for multi-agent systems (MAS) in 6G operator networks. The objective is to model an environment where multiple stakeholders-network operators, regulators, and users-collaborate to achieve optimal resource allocation under diverse and often conflicting constraints. The approach will leverage game theory and reinforcement learning to design serious game-based simulations, where AI agents interact in a competitive and cooperative framework to optimize network deployment, sustainability, and economic viability. The research will also explore novel reward mechanisms balancing local (operator-specific) and global (societal and environmental) objectives. The proposed models will be evaluated through progressive simulation scenarios, addressing challenges such as climate adaptation, regulatory constraints, and cooperative resource allocation in 6G networks.

6.2.2 PhD (CIFRE with CANON CRF): "Surveillance d'une infrastructure de perception coopérative"

Maxime Cancouet's thesis started at Canon Research Centre France (Canon CRF) in April 2023 under a CIFRE agreement. It is focused on the monitoring of a cooperative perception infrastructure. More precisely, the objective is to find and develop means to evaluate the infrastructure-obtained data and provide some proof of trust to the users of these data.

In this scope, Maxime participates in the European research project SELFY (https://selfy-project.eu/) in which the Canon CRF team is involved, with objectives similar to those of the thesis allowing progress in harmony on both the thesis and the project. Indeed, this three-year project involving several European companies and universities aims to develop a toolbox improving the resilience and ensuring the security of data from CCAM systems (Cooperative Connected Automated Mobility).

6.2.3 PhD (CIFRE with Orange Labs): "Embedded artificial intelligence and cellular connectivity for drones: modeling, optimization, and network impacts"

Participants: Antoine Le Borgne, Tayeb LemLouma, Xavier Marjou (OLabs) and Fanny Parzysz (OLabs).

This PhD thesis is conducted in collaboration between the IRISA laboratory and Orange's Architecture for Radio and Core networks (ARC) team, which is responsible for designing the architectures of Orange's future telecommunications networks. Within this framework, the project brings together a wide range of stakeholders, including network architects, standardization experts involved in organizations such as W3C, IETF, and 3GPP, as well as researchers, Ph.D. students, apprentices, and trainees, fostering a multidisciplinary and collaborative research environment.

The objective of the thesis is to model and evaluate the impact of connected drone trajectories on radio access networks (RAN), taking into account both road infrastructures and cellular coverage from one or multiple operators. The proposed approach aims to integrate planned drone routes in order to (a) minimize traffic load and congestion on a given RAN whether limited to Orange's infrastructure or extended to multi-operator (MNO) scenarios, (b) reduce interference with sensitive or restricted areas, and (c) ensure a high Quality of Experience (QoE) for drone-based User Equipment (UE) as well as for conventional terrestrial users. The developed models will support the analysis and optimization of network performance under emerging aerial mobility use cases, contributing to more efficient and resilient future network architectures.

6.3 Collaborations

6.3.1 Collaboration with Udayana University (Bali/Indonesia)

In 2025, we initiated a new international collaboration with Udayana University (Indonesia), in particular with Prof. Indra Er Ngurah. This collaboration focuses on the simulation of complex traffic scenarios involving both vehicles and vulnerable road users (VRUs), with the integration of communication aspects in the simulation models.

The objective is to better understand and evaluate cooperative mechanisms between vehicles and infrastructure to improve the safety of vulnerable users in dynamic environments. This work is aligned with our research on cooperative systems and localized data exchange.

Prof. Bonnin visited the Udayan University department of Electrical Engineering in October 2025, and this collaboration has already resulted in a joint publication [4]. It will be further strengthened through a three-month research stay of one of our PhD students (Manoj Gudi) at Udayana University.

6.3.2 Collaboration with Tokyo University (Tokyo/Japan)

Following the work initiated with Juliette Grosset and a joint publication in 2024, we aim to further develop our collaboration with Tsukada'Jab at Todai by extending our

research toward mobile robotics in industrial environments. This collaboration builds on our expertise in cooperative systems and 5G-V2X, which are of particular interest for enabling reliable and efficient communication in industrial robotic applications when leveraging on a 5G Private network. To strengthen this collaboration, we plan to co-supervise a Master's thesis in 2026, and a research visit of one of our team members is scheduled for summer 2026.

6.3.3 Collaboration with Prof. Bessam Abdulrazak of Sherbrooke University

We develop a strong collaboration with UniversitÃ© de Sherbrooke (Canada), in particular with Prof. Bessam Abdulrazak, who is an associate researcher at IMT Atlantique within the E4SE team. This collaboration has already led to several joint project submissions, including a PRCI project submitted unsuccessfully to ANR in 2024 and two European project proposals in 2025 and 2026.

This collaboration brings key expertise in federated learning, which is a major approach for distributing learning processes across devices in the environment. It allows data to be processed and aggregated locally, so that only consolidated information is shared, enabling global optimization while preserving scalability and reducing communication overhead. This approach is particularly relevant for our research on cooperative systems and local interactions.

In our most recent project proposal (MOTECT), we jointly investigate use cases related to the mobility of vulnerable individuals in urban environments. The objective is to design adaptive services that can leverage distributed data and learning capabilities without requiring heavy centralized infrastructures. In this context, we aim to enable systems to continuously learn from their environment in order to dynamically adapt services to the evolving needs and conditions of users.

Prof. Abdulrazak visited our team in December 2025.

6.3.4 Collaboration with Hospitalité Saint Thomas de Villeneuve (HSTV)

In the context of extending our research toward eHealth applications (and domiciliary approach), we have initiated a collaboration with HSTV (Hospitalité Saint-Thomas de Villeneuve), which provides access to a living lab environment. This setting allows us to experiment with real-life conditions and to evaluate technological solutions in close interaction with users and healthcare professionals.

We explore the use of localized data processing and cooperative systems to support vulnerable individuals. In particular, we focus on technological solutions aimed at improving the safety of people suffering from cognitive disorders, such as Alzheimer's disease, during their movements both inside facilities and in outdoor environments. In this context, we involved the HSTV's Living Lab in a European project proposal (AGORAE) we submitted in 2025. This work is also supported through student projects [15] and Master-level activities, which allow us to prototype and evaluate innovative solutions, while strengthening the link between research, education, and real-world applications.

7 Dissemination

7.1 Promoting scientific activities

7.1.1 Scientific Events Selection

Member of Conference Program Committees

- F. Weis: PC Member eHPWAS'25
- J.-M. Bonnin: PC Members of eHPWAS'25, PIMRC'25, DATA'25, ICLAMP'25
- T. Lemlouma: Organizer and General Chair of the 13th International Workshop on e-Health Pervasive Wireless Applications and Services (eHPWAS 2025) in conjunction with the 21st IEEE WiMob conference (Core Rank B), Marrakesh, Morocco - October 20, 2025.
- T. Lemlouma: Tutorial Chair for the IEEE 44th International Conference on Consumer Electronics (ICCE 2026). Theme: Extended Intelligence with Sustainable Embodied AI Everywhere (Smart, Connected, and Sustainable AI-based Consumer Technologies) February 3-5, 2026, Dubai, UAE.

7.1.2 Invited Talks

- J.-M. Bonnin: 27/01/2025, 4h, Talk on Collaborative autonomous vehicles, ENSSAT, Lannion
- J.-M. Bonnin: 29/04/2025, ID4Mobility Round Table "CybersécuritÃ© du véhicule", Rennes
- J.-M. Bonnin: 9/10/2025, Talk "Ephemeral Local Interactions: A Paradigm Shift for Smarter Environments?", ICSGTEIS'25, Denpasar, Indonesia

7.1.3 Leadership within the Scientific Community

- P. Couderc: Member of the CSV board of "Images et réseaux" cluster
- J.-M. Bonnin: Head of PRACom (Cluster on Advanced Research in Communication)
- J.-M. Bonnin: Conseil de perfectionnement de l'ECAM
- J.-M. Bonnin: Co-director of the Knowledge in Society program at CUT (Center for Unframed Thinking) by RSB (Rennes School of Business).
- J.-M. Bonnin: Member of the scientific committee of the Id4Mobility cluster

7.1.4 Scientific Expertise

- J.-M. Bonnin: Expert for several national research programs: Cyprus, Wallonie, Canada, Japan, French

7.1.5 Research Administration

- J.-M. Bonnin: Elected member of Tenure and Promotion Committee (IMT Atlantique)

7.2 Teaching, supervision

7.2.1 Teaching

For researchers, all activities are given. For professors and assistant professors, only courses at the M. Sc. level are listed.

- J.-M. Bonnin: (24h) (Continuous training: Coopetative ITS architecture, Autonomous vehicles
- J.-M. Bonnin: (20h) Master Smart Mobility : Communication for cooperative ITS (Ecoles des Ponts, Telecom Paris)
- J.-M. Bonnin: M2/M3 (40h) : Smart Cities and Intelligent Transportation Systems

7.2.2 Supervision

- PhD: Antoine Le Borgne, Embedded artificial intelligence and cellular connectivity for drones: modeling, optimization, and network impacts, Tayeb LemLouma, Xavier Marjou and Fanny Parzysz (defended on November 19, 2025)
- PhD in progress: Hassan Hammoud, Agile Data Collection for Smart Agriculture, Frédéric Weis and Jean-Marie Bonnin (to be defended in 2026)
- PhD in progress: Mariam Issa, Mediation infrastructure for ephemeral interactions in smart environments, Paul Couderc and Jean-Marie Bonnin (to be defended in 2026)
- PhD in progress: Maxime Cancouet, Surveillance d'une infrastructure de perception coopérative, Jean-Marie Bonnin (to be defended in 2026)
- PhD in progress: Franck Xu, Cooperative AI for Future Sustainable Networks, Tayeb Lemlouma, Jean-Marie Bonnin
- PhD in progress: Manoj Gudi, Hybridization of 5G-V2X with Other Communication Technologies in Cooperative ITS, Frédéric Weis, Jean-Marie Bonnin
- PhD in progress: Hadi Houssainy, roactive Resource Allocation for Cooperative Connected and Automated Mobility (CCAM) under 5G Networks, Bruno Stévant, Jean-Marie Bonnin

7.2.3 Juries

- J.-M. Bonnin: Jury Member, Antoine Le Borgne, "Évaluation et modélisation de l'impact des drones connectés sur un réseau cellulaire", 19/11/2025

- J.-M. Bonnin: Commmittee Member, Victor Manuel Garcia Martinez, "Time-Critical Digital Twin Infrastructure: A Data Model and Synchronization Analysis Toward Vulnerable Road Users Safety in Road Intersection", 16/12/2025, Sau Paulo (visio)

- J.-M. Bonnin: CSI Thomas Le Beux
- J.-M. Bonnin: CSI David Kolar
- J.-M. Bonnin: CSI Leonardo Daou
- P. Couderc: CSI Mouhamadou Falilou Ball
- T. Lemlouma: CSI Zobilah Abdullah Mohammed Saghir

8 Bibliography

Articles in referred journals and book chapters

[1] J.-M. Bonnin, F. Weis, "Données géolocalisées, souveraineté et indépendance stratégique", *Annales des Mines - Enjeux Numériques*, 31, 2025, p. 54–59.

[2] J. Grosset, M. Djoko-Kouam, A.-J. Fougères, J.-M. Bonnin, "Fuzzy Agent-Based Simulations of Cooperative Strategies for Task Allocation, Collision Avoidance, and Battery Charging Management of Autonomous Industrial Vehicles", *International Journal On Advances in Systems and Measurements 18*, 1&2, 2025, p. 8–18, https://imt-atlantique.hal.science/hal-05220996.

[3] J. Grosset, A.-J. Fougères, O. Oukacha, M. Djoko-Kouam, J.-M. Bonnin, "Simulation of Autonomous Industrial Vehicle Fleet Using Fuzzy Agents: Application to Task Allocation and Battery Charge Management", *American Journal of Management 25*, 1, February 2025, https://imt-atlantique.hal.science/hal-05010040.

Publications in Conferences and Workshops

[4] N. P. Amanda Saraswati, N. I. Er, G. Sukadarmika, W. G. Ariastina, J.-M. Bonnin, "Towards V2X-Enabled Vulnerable Road Users Protection: Baseline Performance Evaluation of a Fundamental Kinematic Model for CAM-Based Trajectory Prediction at Road Intersections", *in : 2025 International Conference on Smart-Green Technology in Electrical and Information Systems (ICSGTEIS)*, IEEE, p. 152–158, Denpasar, Indonesia, October 2025, https://hal.science/hal-05536737.

[5] M. Cancouët, H. Ruellan, R. Bellessort, I. Morvan, E. Nassor, H. Hyyti, J.-M. Bonnin, "Mitigating Systematic Errors in Roadside Camera-Based V2X Perception", *in : IEEE Intelligent Transportation Systems Society Conference Management System*, Detroit (MI), United States, June 2026, https://hal.science/hal-05556744.

[6] H. E. H. Chehade, P. Couderc, J.-M. Bonnin, "Dynamic Configuration Adjustment for Improving Reading of high RFID Tags Density", *in : 2025 IEEE International Conference on RFID Technology and Applications (RFID-TA)*, *2025 IEEE International Conference on RFID Technology and Applications (RFID-TA)*, IEEE, p. 1–6, Valence, France, October 2025, https://hal.science/hal-05536747.

[7] M. Gudi, A. Mokdad, J.-M. Bonnin, F. Weis, "SCHC Header Compression for GeoNetworking protocol: Adaptation and Performance Evaluation", *in : IEEE Wireless Communications and Networking Conference 2026*, Kuala Lampur, Malaysia, April 2026, https://hal.science/hal-05528912.

[8] M. Gudi, L. Toutain, J.-M. Bonnin, A. Pelov, "Modelling V2X CAMs in YANG for Interoperability and Management-Efficient Encoding", *in : IEEE/IFIP Network Operations and Management Symposium 2026*, Rome, Italy, May 2026, https://hal.science/hal-05528914.

[9] H. Hammoud, F. Weis, M. Leclerc, J.-M. Bonnin, "Toward a More Realistic Energy Consumption Model for IoT Nodes in Extreme-Edge Computing Environments", *in : IoTBDS 2025, 10th International Conference on Internet of Things, Big Data and Security*, Porto, Portugal, April 2025, https://hal.science/hal-04910952.

[10] M. E. H. Issa, P. Couderc, J.-M. Bonnin, "Inter-Technology Application Data Exchange Based on Advertisement Packets", *in : 9th EAI International Conference on Intelligent Transport Systems*, INTSYS, Marietta, GA, USA, December 2025.

[11] A. Le Borgne, X. Marjou, F. Parzysz, T. Lemlouma, "Estimating the Benefits of a Multi-Operator Approach to Enhance Cellular Connectivity of Drones", *in : 2024 International Symposium on Networks, Computers and Communications (ISNCC)*, IEEE, p. 1–6, Washington DC, France, October 2024, https://hal.science/hal-05010271.

[12] Y.-H. F. Xu, T. Lemlouma, A. Braud, J.-M. Bonnin, "Altruism and Fair Objective in Mixed-Motive Markov Games", *in : AAMAS : the 25th International Conference on Autonomous Agents and Multi-Agent Systems*, Pahos, Cyprus, May 2026, https://hal.science/hal-05534065.

Miscellaneous

[13] R. Bellessort, M. Cancouët, E. Nassor, J.-M. Bonnin, "Method, device, and computer program for monitoring proper operation of sensors within an intelligent transport system", United Kingdom, GB2634088A, April 2025, https://imt-atlantique.hal.science/hal-05536770.

[14] M. Cancouët, E. Nassor, R. Bellessort, I. Morvan, B. Le Houerou, J.-M. Bonnin, "Method, device, and computer program for improving communication in an intelligent transport system", France, EP4521784A1; GB2633369A, March 2025, https://imt-atlantique.hal.science/hal-05536724.

[15] J. R. Reerink-Boulanger, C. Ric, J.-M. Bonnin, "Approche par le Design pour renforcer la liberté d'aller et venir en EHPAD", Colloque IMT - Ingénierie de la santé et du bien-être, May 2025, Poster, https://hal.science/hal-05557936.