Self-Organizing Large Scale IoT Mesh Networks through Distributed Time Synchronization & Cognitive Coexistence

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Mots clés en français: Internet des Objets, réseaux sans fils, réseaux maillés, synchronisation, réseaux industriels.

Mots clés en anglais : IoT, Industrial Networks, Industrial IoT, Mesh Networks, Wireless Networks, Time Synchronization, Cognitive Networks.

Contexte / Impact socio-économique attendu de la thèse (1/2 p env., en anglais ou français)

The Internet of things (IoT) industry is expanding faster than ever, increasing the number of connected devices by short-range radio technologies (e.g., Zigbee, Bluetooth, WiFi) to an estimated volume of 20.6 billion devices by 2026 (Ericsson Mobility Report, Nov. 2020). A prominent factor in this growth is the license-free Industrial, Scientific, and Medical (ISM) frequency bands, which are harmonized worldwide for deploying independent networks without licensing. As a result, this growth is not only increasing the number of IoT systems but also the size of systems to support smart applications and their coexistence/interference scenarios in the same environment. Supporting large-scale wireless mesh IoT networks with interference awareness, while not compromising important performance metrics like throughput, latency, and current consumptions, is key to meet the emerging connectivity demands of smart spaces (e.g., offices, industries).

One of the favorite channel access methods for IoT used in smart commercial or industrial buildings is Time Slotted Channel Hopping (TSCH)-enable mesh networks. TSCH enables small Radio Frequency (RF) footprints as well as the robustness of IoT networks against interference by implementing Adaptive Frequency Hopping (AFH), both being integral to operate in crowded license-free frequency bands. However, TSCH technology requires accurate network-wide time synchronization for synchronous AFH, which becomes a challenge with network size/scale. Apart from AFH, time synchronization is central to executing distributed control and sensing for the underlying applications (e.g., fault/event localization in structural health monitoring). Meanwhile, AFH requires intelligence on coexisting technologies; estimation and prediction of spectral footprints in time, frequency, and space domain of RF interference play a vital role in increasing the robustness and dependability of TSCH systems by blacklisting the interfered radio resources.

In this context, this project will contribute towards designing dependable large-scale low-power wireless mesh networks, with two crucial research elements on establishing and maintaining such networks as:

- Developing scalable and accurate distributed time synchronization schemes for expanding IoT systems.
- Instead of a statistical model for existing reactive AFH schemes, developing proactive AFH, based on radio-map generation with interference detection and learning, to increase reliability and ability to coexist with other IoT systems.

Objectifs scientifiques, positionnement / originalité, continuité avec thèses antérieures (en ce cas expliquer les nouveaux apports attendus) ou nouveau sujet (1 à 2 p. max., en anglais ou français)

A traditional way to achieve time synchronization in mesh networks is to have one centralized time source to which all other actors in the network, which can be located at various hops from the source, synchronize themselves. This eventually breaks down due to accumulating errors at each synchronization hop, putting a limit on mesh network size. The problem can be circumvented by deploying multiple TSCH mesh networks, and interconnecting them through a wired IT infrastructure. However, this approach has many drawbacks in practice, such as installation complexity, costlier maintenance, and limitations in device-to-device communication. Therefore, there is an apparent need for a scalable time synchronization module for large-scale TSCH mesh networks.

The scalability of a time synchronization mechanism depends on: a) **clock stability:** clocks in low-cost IoT devices are driven by low stability oscillators, requiring frequent clock corrections, b) **Time dissemination protocol**: time sources disseminate their sense of time using frequent (depending on devices' clock stability) time-carrying messages, so-called beacons. For a single time source, the intermediate nodes act as time relays to trickle the timing information in the network, and c) **clock estimation algorithm**: is the core part of a synchronization, which uses received past timing beacons, enabling devices to estimate clock offset and keep track of how their time evolves with reference to the timing source. The relative evolution of the time at devices tells how their clocks are skewing.

Therefore, a time synchronization service requires the study of clock stability mechanisms, efficient time dissemination protocols, and clock estimation algorithms that can be configured to the given clock stability of devices. As a single time source creates a single point of failure, accumulates errors with increasing hops (e.g., due to time uncertainty in message propagation, transmission, detection), there is an increasing need for entirely distributed or multi-source synchronization schemes. In these schemes, the time distribution in the network evolves autonomously and the network tries to achieve stability or consensus under the effect of independently wandering clocks.

In this respect, the first part of the project aims to develop new clock stability and estimation techniques, and establish the scalability/stability of alternate multi-source and distributed synchronization schemes.

In unlicensed bands, several technologies compete for spectrum access without an inter-technology coordination mechanism, leading to mutual interference. The interference level exhibits complex dynamics in time, space and frequency, and the network-wise interaction/infliction on a network of interest becomes dynamic, posing severe threats to communication quality. Such coexistence scenarios discourage deploying critical IoT applications (such as industrial monitoring and control) over unlicensed bands unless proper mechanisms for inter-technology coordination or interference avoidance are adopted. Since inter-technology coordination and spectrum collaboration are still at their early development stages, the importance of spectrum sensing and interference mitigation becomes crucial. Currently, there is a high demand for IoT technologies that can solve the overcrowding of devices in the limited frequency spectrum as it would improve the network reliability and dependability.

Spectrum sensing aims at quantifying the spectrum usage statistics or at identifying the interfering signals across a frequency band at a given location. The aggregation of distributed spectrum measurements provides a representation (or map) of interference over a multidimensional radio space and gives insights on how the interference varies within the location of interest. The availability of such maps enables environment-aware medium access approaches, such as interference-aware channel selection and hopping or interference-aware end-to-end routing.

In this respect, the main focus this part of the project is to: a) utilize the time synchronization scheme developed in the first part of the project for synchronized sensing of the wireless spectrum in low-complexity IoT devices, b) use Machine Learning (ML) and Artificial Intelligence (AI) to assist in identifying different radio disturbers, and c) fusing this information for developing near Real-Time (near-RT) interference maps. The goal is to have the new technology integrated into TSCH communication stack for proactive AFH and end-to-end routing decisions.

The overall objective of the project is to develop an autonomous IoT mesh system that can scale in size with the demand and maintain itself in rapidly proliferating radio environments. Importantly, all these tasks must be performed with minimal energy consumption and without affecting the normal operation (i.e., sensing and monitoring the environment) of an IoT network.

Note that these challenges have been identified through our previous PhD projects that took place in Rennes, in the OCIF research team. More specifically, through the theses of Dr. Pascal Thubert, Dr. Tomas Lagos and through the ongoing thesis of Amaury Bruniaux. These works were oriented on providing reliable, available and predictable wireless networking in industrial environments.

Meanwhile, at Mid Sweden University, the doctoral theses of Dr. Simone Grimaldi and Dr. Luca Beltramelli were towards interference detection/mitigation and time synchronization for medium access, respectively, in low-cost IoT devices.

Compétences requises du candidat, adéquation avec domaine scientifique de l'encadrement et complémentarité encadrement (1/2 p max., en anglais ou français)

Required competence for the applicant:

- Signal processing, especially detection and estimation theory for developing clock offset and skew estimators, and interference detection, inference, and radio maps generation.
- Applied mathematics and optimization for clock stability analysis and parameter optimization.
- Embedded system programming for developing and demonstrating the developed components as a system.
- Good understanding of IoT protocol stacks, PHY/MAC layers, and real-time operating systems (e.g., Contiki, FreeRTOS, TinyOS).

Competence of supervisors:

- **Dr. Georgios Z. Papadopoulos**, recipient of the ANR JCJC project, research interests include wireless networks, Industrial IoT, Wireless Battery Management System, Smart Grid, and Moving Target Defense. He has supervised several PhD students in the area of QoS for industrial wireless mesh networks.
- **Dr. Nicolas Montavont** research field is the Industrial IoT, and more particularly how to provide quality of service in IoT. Recently he co-supervised several thesis to propose protocols and algorithms to provide high reliability and bounded delay in IEEE 802.15.4 networks. He also has a strong expertise in experimentations on real-sized platforms like electric cars or smart grids.
- **Dr. Mikael's** main research field is reliable and secure wireless connectivity for industrial automation, mainly for applications such as wireless control and

predictive maintenance. He has been the PI or co-PI in several projects supported by Knowledge Foundation (KKS), SSF, and Vinnova. He has more than 10 years of R&D experience from industry, in various roles such as project manager, senior principal scientist and global research manager of wireless technologies at ABB Corporate Research with main responsibility to drive technology and strategy plans, standardization and innovation in the wireless automation area. He is an inventor of more than 20 patents (pending and granted) owned by ABB.

- **Dr. Aamir’s** research is focused on design to implementation of low-power wireless connectivity for massive IoT, RF coexistence in unlicensed bands, over-the-air time synchronization in WSNs and 5G, and context-aware radio resource allocation for industrial systems.