Analysis of the Impact of Wireless Mobile Devices in Critical Industrial Applications

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Para ama, aita, Gorka

Y para Ander

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Abstract

The main objective of the thesis is to study the impact of mobile nodes in industrial applications with strict reliability and time constraints in both centralized and decentralized topologies. Considering the harsh wireless channel conditions of industrial environments, that goal implies a considerable challenge. In order not to compromise the performance of the system, a deterministic Real-Time (RT) communication protocol is needed, along with a mechanism to deal with changes in the topology due to the movements of the wireless devices.

The existing wireless standard technologies do not satisfy the requirements demanded by the most critical industrial applications such as Distributed Control Systems (DCS) and, thus, wired communication cannot be directly replaced by wireless solutions. Nevertheless, the adoption of wireless communications can be seen as an extension to the existing wired networks to create hybrid networks with mobility requirements. The design of a proper communication solution depends mainly on the choice of the Medium Access Control (MAC) protocol, which is responsible for controlling access to the medium and thereby plays a vital role in decreasing latency and packet errors. Furthermore, the changes in the topology due to the movement of the wireless devices must be managed correctly in order not to affect the performance of the entire network.

In this doctoral thesis, a hybrid centralized architecture designed for industrial applications with strict requirements in terms of robustness, determinism and RT is proposed and evaluated. For that, a wireless RT MAC scheme based on the IEEE 802.11 physical layer is proposed along with a Real-Time Ethernet (RTE) MAC scheme. This hybrid system ensures seamless communication between both media.

With the aim of including mobile devices in the proposed architecture, a soft-handover algorithm is designed and evaluated. This algorithm guarantees an uninterrupted communication during the handover process without the need for a second radio interface and with a reduced growth in network overhead.

Finally, the impact of mobile nodes in a decentralized wireless topology is analysed. For that, the Self-Organizing Time Division Multiple Access (STDMA) protocol is evaluated to analyse its viability as an alternative to carrying out a handover in industrial applications without centralized systems.

Resumen

El objetivo principal de la tesis es estudiar el impacto de los nodos móviles en las aplicaciones inalámbricas industriales con requisitos estrictos de tiempo y robustez tanto para topologías centralizadas como descentralizadas. Este objetivo supone un gran desafío dadas las adversas condiciones del canal inalámbrico en los entornos industriales. Para no comprometer el rendimiento del sistema, es necesario un protocolo de comunicación determinista y con garantías de tiempo real, junto con un mecanismo para hacer frente a los cambios en la topología debido al movimiento de los dispositivos inalámbricos.

Las tecnologías estándar inalámbricas existentes no satisfacen los requisitos exigidos por las aplicaciones industriales más críticas, como los Sistemas de Control Distribuido (DCS - Distributed Control Systems) y, por lo tanto, las comunicaciones cableadas no pueden ser reemplazadas directamente por soluciones inalámbricas. Sin embargo, la adopción de las comunicaciones inalámbricas puede verse como una extensión de las redes cableadas existentes con el objetivo de crear redes híbridas con requisitos de movilidad. El diseño de una solución de comunicación adecuada depende principalmente de la elección del protocolo de control de acceso al medio (MAC - Medium Access Control), el cual, desempeña un papel vital en la disminución de la latencia y del número de paquetes erróneos. Además, los cambios en la topología debidos al movimiento de los dispositivos inalámbricos deben gestionarse correctamente para que el rendimiento de toda la red no se vea afectado.

En esta tesis doctoral se propone y se evalúa una arquitectura híbrida centralizada diseñada para aplicaciones industriales con requisitos estrictos de robustez, determinismo y tiempo real. Para ello, se propone un esquema MAC inalámbrico con garantías de tiempo real basado en la capa física IEEE 802.11 junto con un esquema MAC basado en Ethernet en tiempo real (RTE - Real-Time Ethernet). Este esquema híbrido garantiza una comunicación continua entre ambos medios de comunicación.

Con el objetivo de incluir dispositivos móviles en la arquitectura propuesta, se propone y evalúa un algoritmo de soft-handover. Este algoritmo garantiza una comunicación ininterrumpida durante el proceso de handover sin la necesidad de una segunda interfaz de radio y con un aumento reducido de la sobrecarga de la red.

Finalmente, se analiza el impacto de los nodos móviles en una topología inalámbrica descentralizada. Para ello, se evalúa el protocolo del estado del arte Self-Organizing Time Division Multiple Access (STDMA) con el objetivo de analizar su viabilidad como alternativa para realizar un handover en las aplicaciones industriales sin sistemas centralizados.

Laburpena

Tesi honen helburu nagusia, nodo mugikorrek fidagarritasun eta denboraren aldetik baldintza ugari eskatzen duten aplikazio industrial zentralizatu eta deszentralizatuetan duten eragina aztertzea da. Eremu industrialetako haririk gabeko kanaletan ematen diren komunikazioetarako baldintza bereziki aurkakoak direla medio, helburu honek erronka handia sortzen du. Sarearen errendimendua arriskuan ez jartzeko, determinista eta denbora errealeko komunikazio protokolo bat beharrezkoa da, haririk gabeko nodoen mugimenduaren ondorioz topologiaren aldaketei aurre egiteko mekanismo batekin batera.

Haririk gabeko teknologia estandarrek ez dute aplikazio industrial kritikoenek dituzten baldintzak betetzen eta, beraz, kable bidezko komunikazioak ezin dira haririk gabeko sistemekin ordezkatu. Hala ere, haririk gabeko komunikazioen erabilpena jadanik existitzen diren kable bidezko komunikazioen hedadura bezala kontsidera daiteke, mobilitate baldintzak dituzten sare hibridoak sortuz. Komunikazio sistemaren diseinu egokia Medium Access Control (MAC) protokoloaren hautaketa zuzenean oinarritzen da gehien bat, sarbidea kontrolatzeaz arduratzen baita, honela ezinbesteko papera izanik latentzian eta pakete erroreen murrizketan. Horretaz aparte, bai sare zentralizatu eta deszentralizatuen kasuan, haririk gabeko nodoen mugimenduek sortutako tipologia aldaketak azkar eta zuzen kudeatu behar dira sare osoko errendimenduak kalterik ez jasateko.

Doktore tesi honetan, fidagarritasun zorrotz, determinismo eta denbora-errealeko baldintzak dituzten industria aplikazioetarako arkitektura hibrido zentralizatu bat proposatu eta ebaluatu da. Horretarako, IEEE 802.11 maila fisikoan oinarritutako haririk gabeko MAC eskema bat proposatu da, Real-Time Ethernet-en (RTE) oinarritutako MAC eskema batekin batera. Eskema hibrido honek bi komunikabideen artean etengabeko komunikazioa bermatzen du.

Proposatutako arkitekturan nodo mugikorrak kontuan hartu ahal izateko, soft-handover algoritmo bat proposatu eta ebaluatu da. Algoritmo honek etenik gabeko komunikazioa bermatzen du handover prozesuan zehar bigarren irrati interfaze baten beharrik gabe eta sareko gainkarga oso gutxi handituz.

Azkenik, nodo mugikorrek duten eragina haririk gabeko topologia deszentralizatuetan aztertu da. Horretako, bibliografiako Self-Organizing Time Division Multiple Access (STDMA) protokoloa ebaluatu da industrial aplikazioetako sistema zentralizatuen handover mekanismoaren alternatiba gisa.

Declaration of Originality

I hereby declare that the research recorded in this thesis and the thesis itself were developed entirely by myself at the HW and Communication Systems Area, in the Communication Systems Team, at Ikerlan Technology Research Centre.

Zaloa Fernández Ganzabal
Team of Communication Systems
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Contents

List of Figures

List of Tables

Acronyms

3GPP	*3rd Generation Partnership Project*
5G	*Fifth Generation*
ACK	*Acknowledgement*
AIS	*Automatic Identification System*
AMR	*Autonomous Mobile Robots*
AP	*Access Point*
BE	*Best-Effort*
BER	*Bit Error Rate*
CAP	*Contention Access Period*
CDF	*Cumulative Distribution Function*
CDMA	*Code Division Multiple Access*
CFP	*Contention-Free Period*
CSMA	*Carrier Sense Multiple Access*
CSMA/CA	*Carrier Sense Multiple Access with Collision Avoidance*
CSMA/CD	*Carrier Sense Multiple Access with Collision Detection*
CTS	*Clear-To-Send*
DCF	*Distributed Coordination Function*
DCS	*Distributed Control System*
DL	*Downlink*
DSRC	*Dedicated Short-Range Communications*
DTB-MAC	*Dynamic Token-Based Medium Access Control*
EDCA	*Enhanced Distributed Channel Access*
EP-MAC	*Enhanced Priority Medium Access Control*
FA	*Factory Automation*
FCS	*Frame Check Sequence*
FDD	*Frequency Division Duplex*
FDMA	*Frequency Division Multiple Access*
FT	*Fast Basic Service Set Transition*
GPS	*Global Positioning System*
HCCA	*Hybrid Coordination Function Controlled Channel Access*
HO	*Handover*
HPIS	*High-Priority Indication Space*

iPCF	*Industrial Point Coordination Function*
IRT	*Isochronous Real-Time*
IS	*Intermediate System*
ITU	*International Telecommunication Union*
iWLAN	*Industrial Wireless Local Area Network*
IWSAN	*Industrial Wireless Sensor and Actuator Network*
LTE	*Long-Term Evolution*
MAC	*Medium Access Control*
MIMO	*Multiple-Input Multiple-Output*
NACK	*Negative acknowledgement*
NCS	*Networked Control Systems*
NEP	*Network Entry Packet*
NLOS	*Non-Line-of-Sight*
OFDM	*Orthogonal Frequency Division Multiplexing*
OFDMA	*Orthogonal Frequency Division Multiple Access*
OSI	*Open System Interconnection*
PA	*Process Automation*
PCF	*Point Coordination Function*
PER	*Packet Error Rate*
PIAT	*Packet Inter-Arrival Time*
PLC	*Programmable Logic Controller*
PLR	*Packet Loss Rate*
QoS	*Quality of Service*
RATDMA	*Random Access Time Division Multiple Access*
RA-TDMA	*Reconfigurable and Adaptive Time Division Multiple Access*
RA-TDMA+	*Ad-hoc Reconfigurable and Adaptive Time Division Multiple Access*
RC	*Rate-Constrained*
RMS	*Root Mean Square*
R_r	*Report rate*
R_{SI}	*Selection Interval Ratio*
RSSI	*Received Signal Strength Indicator*
RSU	*Roadside Unit*
RT	*Real-Time*
RTE	*Real-Time Ethernet*
SIFS	*Shortest Interframe Space*

s_{NI}	*Nominal Increment*
SNR	*Signal-to-Noise Ratio*
s_{NS}	*Nominal Slot*
s_{NSS}	*Nominal Start Slot*
s_{NTS}	*Nominal Transmission Slot*
SOD	*Slot Occupation Distribution*
SPS	*Semi-Persistent Scheduling*
s_{SI}	*Selection Interval*
SS-MAC	*Slot Stealing Medium Access Control*
ST	*Scheduled Traffic*
STDMA	*Self-Organizing Time Division Multiple Access*
TAS	*Time-Aware Shaper*
TDMA	*Time Division Multiple Access*
TSN	*Time Sensitive Networking*
TT	*Time-Triggered*
TT-Ethernet	*Time-Triggered Ethernet*
UL	*Uplink*
V2I	*Vehicle-to-Infrastructure*
V2V	*Vehicle-to-Vehicle*
VANET	*Vehicular ad-hoc networks*
WAVE	*Wireless Access in Vehicular Environments*
WIA-FA	*Wireless Networks for Industrial Automation – Factory Automation*
WIA-PA	*Wireless Networks for Industrial Automation – Process Automation*
WISA	*Wireless Interface for Sensor and Actuator*
WSAN	*Wireless Sensor and Actuator Networks*

Chapter 1

Introduction

In this chapter, the context in which this doctoral thesis has been carried out is explained. First, the motivation that has led the author to the realization of this work and the main objectives of this research work are introduced. The contributions of the thesis are then presented and finally, the structure of this doctoral thesis report is outlined.

1.1 Motivation

Wireless technologies have been bringing new opportunities and challenges for industrial automation. That is why in recent years, Industrial Wireless Sensor and Actuator Networks (IWSAN) have emerged as a suitable solution for a wide range of industrial applications. IWSAN based solutions provide significant cuts in the deployment, implementation and maintenance costs and greater flexibility. Given these advantages, there is a growing interest in the development and implementation of wireless technologies for industrial applications. Applications with mobile devices or with mobile parts can especially benefit from wireless communications. In some of the industrial applications determinism and Real-Time (RT) communication are crucial, as, for example, in Process Automation (PA) and Factory Automation (FA) applications.

PA applications are characterized by having relatively slow and continuous processes, in which large amounts of data are exchanged. So, their RT and latency requirements are more relaxed. On the contrary, FA applications involve machines that perform discrete actions, such as assembly lines, where closed-loop control systems have strict requirements in terms of RT and latency because they perform very precise operations.

Traditionally, industrial sensors and actuators have been using wired communications. So, to replace wired communications with wireless communications in the most critical industrial applications, these must guarantee RT requirements, determinism and very high reliability. Moreover, wireless communications are more vulnerable than wired ones, due to the shared medium where wireless networks communicate and channel conditions such as path loss, shadowing and fading. The existing wireless standard technologies do not satisfy the requirements demanded by the most critical industrial applications belonging to FA applications such as Distributed Control Systems (DCS) and, thus wired communication cannot be directly replaced by wireless solutions. FA applications such as closed-loop control or mobile robots require an end-to-end delay below 1ms, Packet Loss Rate (PLR) at application level from 10^{-6} to 10^{-12} and a maximum jitter of 1 ms [1], [2].

Nevertheless, the inclusion of mobile devices in wired networks is usually difficult. In many scenarios, where wire deployment is not possible because of mobility, the use of wireless communication is indispensable. Thus, the adoption of wireless communications can be seen as an extension to the existing wired networks, hence creating hybrid wired/wireless networks.

The integration of both networks in industrial applications is not trivial, because they must provide strict reliability and time constraints to have a seamless coexistence. Moreover, to achieve this, the time constraints of the application, the packet structure and the wireless communication system latency must be considered.

Consequently, having a communication system that meets the strict requirements of FA applications and provides high enough throughput, while supporting wireless mobile devices, is a complex task. The design of a proper communication solution depends mainly on the choice of the Medium Access Control (MAC) protocol, which is responsible of controlling access to the medium, and thereby plays a vital role in decreasing latency and minimizing the Packet Error Rate (PER). Besides that, the way in which the network is organized and managed must be taken into account both to reduce the delay and packet errors.

In centralized networks, Access Points (AP) are needed to coordinate the access to the wireless medium enabling predictable delays. However, the need for an AP limits the flexibility of the application and implies having a handover algorithm to deal with AP changes due to the movement of the wireless nodes. In distributed or ad-hoc networks, the nodes communicate with each other without relying on a centralized AP and the nodes themselves are responsible for managing the access to the medium. Note that both in centralized and distributed networks, the changes in the topology due to the movement of the wireless devices must be managed correctly in order not to affect the performance of the entire network.

1.2 Objectives

The main objective of the thesis is to study the impact of mobile nodes in industrial applications with strict reliability and time constraints in both centralized and decentralized topologies. For that, besides taking into account mechanism to deal with changes in the topology due to the movement of the wireless devices, a deterministic RT communication protocol is needed in order to guarantee the demanded requirements. To achieve this objective, several particular objectives have been defined:

- To propose and to evaluate a centralized hybrid RT MAC scheme for Distributed Control Systems with mobility requirements.
- To propose and to evaluate a handover algorithm for the proposed centralized hybrid MAC scheme in order to incorporate mobile devices to the architecture. The proposed handover algorithm must guarantee uninterrupted communication during the handover process.
- To analyse how the changes in the topology due to the movement of the wireless devices are managed with the defined centralized hybrid MAC scheme along with the proposed soft-handover algorithm.
- To analyse the viability of a state-of-the-art distributed MAC protocol for its use in FA applications with mobility requirements in order to carry out handovers without centralized systems.

1.3 Contributions of the thesis

In this section, the main contributions of the developed research work are described. Also, the publications associated with the different contributions are indicated:

- A hybrid centralized architecture designed for scenarios with strict requirements in terms of robustness, determinism and RT is proposed. For that, a wireless RT MAC scheme based on the IEEE 802.11 physical layer is proposed along with a Real-Time Ethernet (RTE) MAC scheme. This hybrid scheme ensures a seamless communication between both media. This contribution has been published in [3], [4].

- A soft-handover algorithm is proposed that guarantees uninterrupted communication during the handover process without the need for a second radio interface and with a reduced growth in network overhead. To avoid any interruption in the communication, a handover algorithm in which the wireless node that initiated the handover process will momentarily have time intervals assigned in the superframe of both the current and target APs is proposed. The results of this contribution have been partially published in [5]. An extended analysis and evaluation of the proposed soft-handover algorithm is going to be submitted to IEEE Access journal:

> Z. Fernández, Ó. Seijo, M. Mendicute and I. Val, "Analysis and Evaluation of a Hybrid Architecture for Distributed Control Systems with Mobility Requirements".

- The self-organization characteristic facilitated by Self-Organizing Time Division Multiple Access (STDMA) protocol is evaluated to analyse its viability as an alternative to carrying out a handover without centralized systems in FA applications. The results of this contribution have been partially published in [6]. An extended analysis and evaluation of the STDMA protocol for industrial scenarios is going to be submitted to IEEE Access journal:

> Z. Fernández, M. Mendicute, E. Uhlemann, A. Balador and I. Val, "Interference Analysis of STDMA When Used in Industrial Scenarios".

A complete list of the publications conducted during the research is included in Appendix A.

1.4 Structure of the thesis

The remainder of this document is organized as follows:

Chapter 2 summarizes the background and related work on wired and wireless industrial communications. Requirements of industrial applications are described, a review of the current MAC protocol for industrial applications is provided. Given the research field of this investigation, a general analysis of the bibliography on hybrid networks and industrial wireless networks with mobility requirements is also provided.

In Chapter 3 a hybrid wired/wireless RT MAC scheme is proposed with the aim to expand the wired network used in industrial control applications to a wireless domain. The proposed MAC scheme focuses on guaranteeing the robustness and determinism required by hybrid Distributed Control Systems. In addition to evaluating the performance of the proposed hybrid scheme through simulations, a theoretical analysis is made to study the validity of the proposed wireless MAC scheme.

In Chapter 4 a soft-handover algorithm is proposed in order to manage the changes in the topology due to the movement of the wireless devices in the hybrid MAC scheme proposed in Chapter 3. This handover algorithm guarantees uninterrupted communication during the handover process without the need for a second radio interface and with a reduced growth in network overhead network overhead. The performance of the proposed soft-handover algorithm is evaluated through simulation and its performance is compared with another handover algorithm in the literature.

In Chapter 5 an extensive simulation based evaluation of the STDMA protocol is carried out under a time-variant industrial channel in presence of variable Doppler shift in order to assess its suitability for industrial applications. Given its self-organization ability, has been chosen STDMA as an alternative to carry out handovers with centralized systems like the one proposed in Chapter 4.

Finally, Chapter 6 summarizes the work done and the main conclusions obtained, as well as the future lines that can serve to complete and expand the work presented in this doctoral thesis. Additionally, a complete list of the publications conducted during the research has been included in Appendix A.

Chapter 2

Background and related work

In this chapter, a general analysis of the state-of-the-art and some theoretical background related to the work introduced in this thesis are provided. In this bibliographic review, both wired and wireless communication techniques for industrial applications have been considered, with the focus on wireless ones. This is because the latter involve a much greater complexity in terms of ensuring the requirements of industrial applications due to the shared wireless channel.

First of all, we start defining industrial applications as well as their main requirements. In Section 2.2, the definition of an industrial communications network is given and the main protocols used in both wired and wireless industrial networks are defined. In Section 2.3, several MAC schemes whose objective is to provide reduced PER and end-to-end delay are analysed. Then, in Section 2.4, hybrid industrial networks are described as well as their benefits. Finally, in Section 2.5, related works on wireless networks with mobility requirements are analysed, which comprise handover mechanisms, mobile ad-hoc networks and vehicular communications.

2.1 Industrial communications

Not all industrial communication systems are equal in terms of RT requirements or criticality of the data to be transmitted and that it is why industrial automation is divided mainly into two categories as stated in Chapter 1: PA and FA [7]. The applications in PA are related to monitoring and diagnosis of processes and elements. The manufacture of chemical, oil or gas products, heating, cooling or pumping procedures and machinery monitoring are typical PA applications. In contrast, FA applications are typically characterized by RT control of systems that perform discrete actions such as assembly lines and they involve motion control. The applications belonging to FA have strict requirements in terms of RT and reliability due to the precise operations they perform [8]. FA applications, such as closed-loop control or mobile robots, require an end-to-end delay below 1ms, PLR at application level from 10^{-6} to 10^{-12} and a maximum jitter of 1 ms. In addition, the cycle time of the system is in the range of 50 µs – 1 ms, the coverage area varies between 10 and 100 meters, while the devices can move at a maximum speed of 30 km/h. Moreover, these applications do not require a large number of devices (10 – 100 devices) and the amount of data to be sent per packet is reduced (15 – 64 bytes) [1], [2], [9], [10].

In contrast, PA applications demand more relaxed requirements such as an end-to-end delay in the range of 10 – 100 ms and PLR of 10^{-3} – 10^{-4}. The required update time in those applications is in the range of 1 ms – 5 s, the coverage area is 100 – 500 meters and the devices can move at a maximum speed of 5 km/h. Finally, both the number of supported devices (100 – 300 nodes) and the amount of data to be sent per packet (30 – 1500 bytes) are higher than in FA applications [1], [2], [9], [10].

The following are the main requirements of industrial communications, being stricter for the most critical industrial applications [1], [11]–[13]:

1. **Reliability**: depending on the industrial application, packet losses can cause from economic losses due to an unwanted stoppage in production to serious consequences, such as human injuries or loss of machinery. Therefore, reliable systems with a reduced error probability are sought.

2. **RT communication**: nowadays, most industrial applications have some kind of RT requirement. They do not only require a successful communication but have also a deadline to meet. Depending on the RT requirements, industrial applications can be classified into non-RT, soft RT, hard RT or isochronous RT applications. While non-RT applications, such as those in charge of monitoring, have no requirement regarding deadlines, the other three application types have some deadline requirements. The deadlines of the soft RT applications (mostly applications that are part of PA) do not compromise the behaviour of the system. In contrast, both hard RT and isochronous RT applications (applications that are part of FA) have to meet strict deadlines not to cause an error in the application. Moreover, isochronous RT applications have more restricted requirements in terms of jitter and latency than hard RT applications.

3. **Determinism**: for a system to be deterministic, it is necessary to be able to reproduce and predict all the access to the medium considering the control cycles of the process. This requirement is important especially in industrial applications with strict time restrictions given that in these, the information received after the deadline is considered erroneous, and can cause from the interruption of the process or service to injuries or losses of machinery. For the same reason, in these applications, a reduced latency is needed.

4. **The payload of the transmitted packets**: in general, the packets exchanged in industrial communications have a reduced size. As stated previously, in the case of FA applications, the data to be sent per packet is lower than 64 bytes [1], [2], [9], [10]..

5. **Time synchronization**: temporal accuracy is necessary to determine when the information has been obtained, which requires a global time base. Thanks to time synchronization, the devices of the systems will be able to use the transmission medium in the most efficient way possible and guarantee a deterministic communication.

6. **Heterogeneity**: this term can be applied to networks (the coexistence of different networks in the same system) or to the traffic to be transmitted (the existence of different types of traffic in the same network).

   a. **Network heterogeneity**: given the current interest of the industry in the use of wireless communications, heterogeneity begins to become a requirement in industrial applications [14]. As mentioned in Chapter 1, wireless communications offer a series of advantages with respect to wired ones, and therefore, more and more technologies are looking for wireless extensions to create hybrid networks from wired networks already deployed.

   b. **Traffic heterogeneity:** all the traffic generated in industrial applications does not require the same treatment. There is traffic that requires RT guarantees and traffic not sensitive to Quality of Service metrics (QoS) as is the case of Best-Effort (BE) traffic. In addition, RT traffic can be both periodic and aperiodic. While periodic RT traffic is characterized by a predictable arrival pattern, the aperiodic RT traffic is very infrequent (for example alarm triggered events) and it is characterized by an unpredictable arrival pattern. Note that the traffic exchanged in industrial applications is mostly periodic [15].

2.2 Communications for industrial applications

An industrial communications network can be defined as a communication system formed by protocols with the ability to manage temporary restrictions and which is used for data transmission between different automation systems.

Given the characteristics of the different devices that form an industrial environment, these are grouped hierarchically according to the information to be transmitted and the requirements to be met as shown in Figure 2.1. The upper levels of this hierarchy are composed of computers that transmit large packets without RT requirements. In these levels, the response time ranges from seconds to days. In contrast, the lower levels of this hierarchy are composed of devices that transmit reduced size packets but with strict RT constraints. The response time, in this case, is in the order of a few milliseconds.

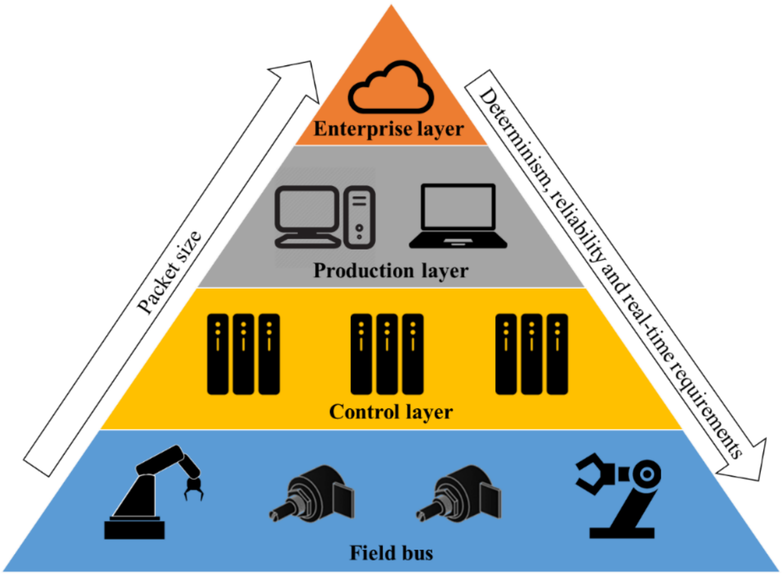


Figure 2.1: Hierarchy of industrial automation.

The lower levels of this hierarchy are those that are directly involved with the control networks and here is where devices such as sensors and actuators used in the different processes are located. The sensors will measure the variables of the process as temperature, pressure or position among others. Meanwhile, the actuators will execute the commands of the control elements to modify the process.

Traditionally, sensors and actuators have been using field buses, whose main advantages are that they can be integrated into complex systems, in addition to the security and the data rate that they offer. However, the adaptation of the IEEE 802.3 standard under the alternatives called Industrial Ethernet or RTE brought a revolution in the way of implement communications in industrial systems. Not only were its high-speed transfer and the vertical integration aspects the reasons to become the substitute for field buses, but also the ability to transmit RT data [16].

2.2.1 Evolution towards Industrial Ethernet

The original IEEE 802.3 Ethernet standard was not designed to perform RT data transmissions, given that its medium access mechanism based on Carrier Sense Multiple Access with Collision Detection (CSMA/CD) that does not guarantee the deterministic behaviour required in industrial applications. So, throughout the years, several RTE solutions have been presented, most of which are adaptations of the existing field buses.

Being FA applications the research subject of this thesis, the analysed RTE solutions focus on the most restrictive RTE class regarding RT characteristics. Those solutions only inherit the physical layer of Ethernet and modify their MAC focusing on approaches based on Time Division Multiple Access (TDMA) to ensure a deterministic communication and efficient data transmission [17]. The most commonly used solutions in industrial applications are briefly described below.

EtherCAT is based on a master/slave architecture, in which the master device cyclically transmits an RT frame through all the slave devices. To achieve maximum performance by ensuring very low and deterministic response times, IEEE 802.3 frames must be processed on-the-fly, i.e. the slave device processes and transmits the frame to the next slave device on the line with a latency lower than 1 ms. To do this, the slaves require special hardware.

SERCOS III is an RTE solution similar to EtherCAT. This solution is also based on a master/slave architecture and the frames are also processed on-the-fly. Unlike in EtherCAT, in SERCOS III the communication is divided into two channels—one dedicated to transmitting RT frames and another to transmitting non-RT frames.

Profinet IO has three classes, based on the RT requirements that are supported. Profinet IRT (Isochronous RT), also called class C, can support critical RT traffic. The communication in Profinet IRT is made through a TDMA-based MAC that allows transmitting isochronous RT frames, RT frames and non-RT IEEE 802.3 frames in an orderly fashion. To achieve this communication, special hardware is required.

Time-Triggered Ethernet (TT-Ethernet) [18] organizes communication using a TDMA MAC scheme. This RTE solution follows the time-triggered paradigm, in which data transmissions will be pre-defined in a schedule that is followed by the devices forming the network. The TT-Ethernet protocol can support the time-triggered traffic, rate constraint traffic and BE traffic.

Finally, the search for a deterministic communication through Ethernet with hard RT guarantees is still a growing research field as of today. Therefore, the IEEE Time-Sensitive Networking task group [19] is working on a set of IEEE technical standards called Time-Sensitive Networking (TSN). The aim of TSN is to provide deterministic communication with RT guarantees over Ethernet. The core of this set of standards is a traffic shaper based on a time-triggered schedule, which is responsible for scheduling the traffic deterministically, getting packets from different priority-based queues. Queues have been previously defined within a schedule, and the transmission of packets will be carried out during the scheduled time window. Thus, all traffic classes may be transmitted over a standard Ethernet network without colliding among them [20], [21]. Moreover, to achieve minimal communication latency or optimal bandwidth usage, TSN also includes a pre-emption mechanism. This mechanism allows interrupting the transmissions of the non-time critical frames to transmit the scheduled priority traffic.

2.2.2 Evolution towards wireless networks

The next logical step in the evolution of communication at the field level is the inclusion of wireless networks. Therefore, over the years and with the Industry 4.0 revolution, the inclusion of wireless communications with RT requirements has been gaining popularity in industrial applications. As mentioned in Chapter 1, though wireless communications offer advantages such as more flexibility concerning physical distribution and deployment in addition to the reduction in the costs derived from the implementation and maintenance [7], [22], they are more vulnerable to phenomena such as path loss, fading or shadowing. Consequently, having a wireless communication system that meets the strict requirements of FA applications is a complex task.

Several of the wireless communication standards used in industrial automation applications are based on the physical layer of the IEEE 802.15.4 standard [23], which specifies both the physical and the MAC layer. Regarding the physical layer, it can operate in two bands, each with a different data rate: In the band 868/915 MHz, a data rate of 20/40 kbps is used whereas in the band of 2.4 GHz a data rate of 250 kbps is used. Regarding the MAC layer, two operation modes are supported: disabled beacon mode, where the MAC layer uses a non-slotted Carrier

Sense Multiple Access with Collision Avoidance (CSMA/CA) system and enabled beacon mode, where a slotted CSMA/CA scheme is used. In this last operation mode, the superframe, which is divided into slots, is composed by a Contention Access Period (CAP) and Contention-Free Period (CFP). At the start of each superframe, as can be seen in Figure 2.2, the network coordinator will send a beacon to synchronize the network. The nodes that form the network can access the CAP period through CSMA/CA, while in the CFP period, each slot will be reserved for a node. Finally, the superframe has a period of inactivity to increase the energy efficiency of the network.

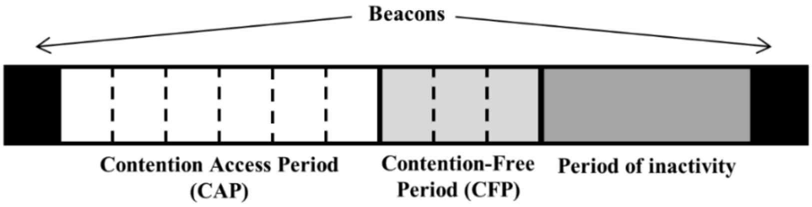


Figure 2.2: Structure of the IEEE 802.15.4 superframe (enabled beacon mode).

The most extended IEEE 802.15.4-based industrial wireless communication standards are summarized below:

ZigBee [24]: this standard takes both the physical and MAC layers of the IEEE 802.15.4 standard and defines a communication layer at level 3 and above in the OSI (Open System Interconnection) model. A ZigBee coordinator will be in charge of controlling the formation and security of networks, besides coordinating access to the wireless medium. Frequency agility is added in ZigBee so that the devices can transmit through the channel with the least interference.

WirelessHART [25]: this standard adopts the physical layer of the IEEE 802.15.4 standard but implements its own data link layer. In WirelessHART the end-to-end latency is ensured through a TDMA medium access mechanism. Each slot defined by the TDMA scheme can be assigned by a specific node or can be shared by several nodes that use CSMA/CA. A network coordinator will be responsible for slot allocation. Moreover, WirelessHART provides end-to-end reliability of 99.9% thanks to the use of features such as channel hopping or the search for alternative paths in case of channel degradation.

ISA 100.11a [26]: this standard implements the physical layer of the IEEE 802.15.4 standard and part of its data link layer. It shares several functionalities with WirelessHART such as the use of TDMA medium access mechanisms and channel hopping. It should be noted that the size of the TDMA slot in ISA 100.11a is configurable, so it is possible that two ISA100.11a devices cannot communicate because they have different slot lengths.

Wireless Networks for Industrial Automation – Process Automation (WIA – PA) [27]: this standard implements the physical layer of the IEEE 802.15.4 standard and part of its data link layer. This standard uses TDMA, Frequency Division Multiple Access (FDMA) and Carrier Sense Multiple Access (CSMA) as medium access mechanisms. Both RT and non-RT packets are considered, and all devices have the same probability of accessing the channel.

It should be noted that none of these standards can be used in the most critical industrial applications [28]: ZigBee is based on CSMA/CA where no time bound can be guaranteed [29]. In the case of WirelessHART, despite guaranteeing a 99.9% end-to-end reliability, it does not deal with packet losses due to link bursts [30]. Both ISA 100.11a and WIA-PA are mainly used for industrial applications with relaxed requirements on latency and RT such as monitoring. In the case of WIA-PA, it does not guarantee that RT packets are going to be sent before those that do not have RT requirements [31] and ISA 100.11a is only able to provide non-critical monitoring and control in applications with latencies greater than 100 ms [29].

Leaving aside the IEEE 802.15.4-based industrial wireless communication standards, the Wireless Interface for Sensor and Actuator (WISA) standard is also used in the industrial environment. Based on the IEEE 802.15.1 (Bluetooth) standard, which operates in the 2.4 GHz ISM band at 1Mb/s, WISA [32] was designed to be used in FA Wireless Sensor and Actuator Networks (WSAN). To coexist with other systems that operate in this band, WISA uses Frequency Division Duplex (FDD) and frequency hopping techniques. WISA uses parallel uplink and downlink links. In the uplink, the nodes use TDMA to transmit the packets to the network coordinator which retransmits to every node through the downlink channel. In the downlink side, the protocol offers mechanisms for assigning priorities [33]. Note that the reliability of WISA is in the order of 10^{-4} and it can offer less than 20 ms end-to-end latency which are not enough for the most critical applications [1], [34].

All previously mentioned standards are based on the physical layer of IEEE 802.15 whose data rate is limited and offers low scalability within a specific cycle time [34]. So, recently, there is an increasing interest in the use of the IEEE 802.11 physical layer in industrial applications given its higher data rate [35]. Wireless Networks for Industrial Automation – Factory Automation (WIA-FA) [36] is the first wireless technology specification developed for high-speed, industrial control applications. This technology is based on the IEEE 802.11 standard and defines a MAC layer based on multiple access mechanisms such as TDMA, FDMA and data aggregation. The proposed MAC layer is designed to guarantee RT and reliable communication between WIA-FA devices. The guaranteed cycle time is in the order of several milliseconds considering several tens of nodes, which makes this technology suitable for some FA applications but not for the most critical ones. Also based on IEEE 802.11 standard, there is the industrial Wireless Local Area Network (iWLAN) [37] technology, which has been developed by Siemens for industrial wireless communication. In order to ensure a deterministic communication, the Point Coordination Function (PCF) used in the MAC layer of IEEE 802.11 standard is redefined as industrial PCF (iPCF). The iPCF relies on a central node, which cyclically polls the rest of the devices in the network. Although iPCF provides coordinated medium access, the polling mechanism overheads the communication affecting the latency of the system. So, the search for a wireless communication protocol that guarantees the strict requirements of FA applications is still a growing research field as of today.

2.3 Medium Access Control (MAC)

The choice of a proper communication solution depends mainly on the design of the MAC protocol, so it plays a vital role in decreasing latency and minimizing the PER [22]. Naturally, the requirements of the industrial communications described in Section 2.1 also must be considered when designing the MAC protocols. Furthermore, to guarantee the RT traffic deadlines and ordered medium access, the MAC layer must be complemented with an appropriate scheduler. Obtaining a feasible schedule for all the RT flows of a complex system is not a trivial task, for several reasons [38]: on the one hand the MAC protocol must manage all the traffic types generated by the industrial systems, which can be RT traffic (periodic, aperiodic, sporadic) or traffic without RT requirements i.e. BE traffic as previously introduced in Section 2.1. On the other hand, the MAC protocol must manage the restrictions imposed by the structure of the superframe.

A widely used MAC mechanism is CSMA. This mechanism is based on listening to the medium before transmitting, thus determining if the channel is free. This mechanism does not guarantee a correct transmission in advance because there is no coordination to avoid collisions. Instead, each node makes its own decision about when to access the channel. Therefore, the use of CSMA is not suitable for the transmission of RT traffic because it does not guarantee deterministic communications. Moreover, there are token-based MAC protocols that, although they can provide predictable medium access, the overload caused by the circulation of the token affects the latency of the system. The same thing happens in polling-based protocols. In contrast, in free contention protocols, the available resources are divided among the devices, so each node uses its own resource without the risk of colliding with others. Those protocols also provide predictable medium access. The free contention protocols are mainly based on MAC mechanisms such as TDMA, FDMA and Code Division Multiple Access (CDMA), being the last two used only in wireless networks. In these mechanisms, a centralized manager is usually responsible for modifying the time intervals, frequencies and codes assigned to each user. Despite this, it must be considered that TDMA must deal with time synchronization, FDMA with frequency generation/filtering and CDMA with precise power control.

Several MACs have been proposed in the literature to be used in industrial applications instead of the existing standards defined in Section 2.2.2. Next, those MAC proposals whose objective is to provide a reduced PER and end-to-end delay, will be analysed. All MACs that do not comply with the RT restrictions mentioned in Section 2.1 are left out of this analysis.

2.3.1 MACs for industrial applications

In [39], [40] GinMAC is proposed, a TDMA-based protocol that considers a tree topology. The TDMA frame sizing is carried out in a static way, being dependent on the number of nodes in the network. The TDMA superframe is composed of 3 types of slots: basic (each node will have an uplink and downlink slot assigned), additional (in case the transmission in the basic slots fails, the additional slots can be used, thus increasing the robustness of the system) and unused (used to increase energy efficiency). An example of a possible GinMAC network and its superframe are shown in Figure 2.3 and in Figure 2.4 respectively.

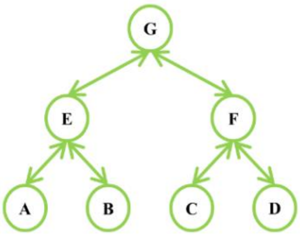


Figure 2.3: GinMAC topology example.

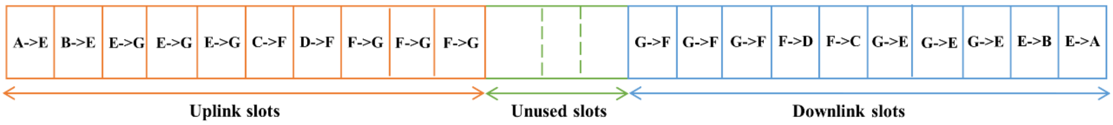


Figure 2.4: GinMAC superframe example.

It should be mentioned that the used slots (both basic and additional) are exclusive and cannot be reused by other nodes in the network. In addition, the length of the frame cannot be greater than the required latency, being a problem in large networks.

Based on GinMAC, DynMAC is proposed in [41], which, based on the properties of cognitive radio, deals with the coexistence with other wireless devices while the specific requirements of critical applications are maintained. In this proposal, a static tree topology in which the nodes can only communicate with their parents is considered. One of the nodes of the network acts as a coordinator and it is responsible for deciding which is the best channel to use. In addition, each node (except the coordinator node) must monitor the PER for a period and if the measured PER exceeds a threshold, the nodes must notify the coordinator node to evaluate if the chosen channel is appropriate.

By means of the hybrid TDMA/CDMA MAC proposed in [42], while the network operates in a collision-free environment, the bandwidth is used efficiently, thanks to a CDMA technique. In this way, the throughput is increased significantly and both the latency and the Bit Error Rate (BER) are reduced. The superframe proposed by this hybrid protocol contains a slot request period, a slots allocation period and several slots for data transmission as shown in Figure 2.5.

Figure 2.5: Hybrid TDMA/CDMA MAC superframe example.

It should be noted that in industrial applications, not all the data generated by the nodes require the same treatment, so it may be interesting to have a medium access mechanism that prioritizes the critical frames. The MACs described above do not support priorities, therefore all packets are treated in the same way.

To solve this, PriorityMAC [29] emerges as a priority-based access protocol that aims to reduce the latency of time-critical traffic. To achieve a priority ordered medium access, a High-Priority Indication Space (HPIS) is inserted before each slot as seen in Figure 2.6. This is composed of two subslots and is used to postpone lower priority traffic. The medium access mechanism is different for each of the four traffic categories supported by this MAC. The two traffic categories with the highest priority, considered as emergency and critical control traffic, can access any slot giving a higher priority to emergency traffic signalling it in the HPIS. However, the two traffic categories with the lowest priority, considered as non-critical control and monitoring traffic, have allocated slots but may not be able to use them if they are being used by a packet of higher priority. Despite this, the backoff time of the second traffic category can be so long that lower priority traffic can access the medium before it.

Figure 2.6: HIPS in the PriorityMAC superframe.

With the aim of overcoming the limitations of PriorityMAC and reducing the latency times of its traffic categories, Enhanced Priority MAC (EP-MAC) protocol is proposed [13]. EP-MAC uses enhanced medium access mechanisms based on those used in PriorityMAC to obtain improved performance. However, like in PriorityMAC, there can still be collisions between same-level priority packets in the case of the three traffic categories with the lowest priority. This is due to the backoff used by their medium access mechanism.

In [43] a TDMA-based MAC called DeMAC is proposed to handle the traffic triggered by events in security systems and closed-loop control related to PA applications. In DeMAC, the coordinator node will transmit the scheduler to the other devices in the network by sending beacons at the start of each superframe. Through this scheduler, each node will have a slot assigned based on the required deadlines for the validity of the data to be transmitted. The nodes of the network will generate two types of traffic (2 priorities). Each control cycle includes two contention-free periods followed by a downlink slot. Thanks to this downlink slot, the latency of the packets is reduced in emergency situations.

In [44] WirArb MAC mechanism is proposed. With a star topology, it offers a high performance guaranteeing a deterministic RT communication. Consider periodic traffic and aperiodic emergency traffic. This MAC pre-assigns a specific arbitration frequency to each node with the purpose of assigned priorities to the nodes. WirArb uses an arbitration phase consisting of two parts, a decision period and an execution period. In the decision period, the requests to access to the wireless channel are processed and the order of transmissions is determined based on the priority of the nodes. Then, in the execution period, the packets are transmitted according to the order set in the previous period. Given that the packets follow the order defined in an earlier stage, the transmission of the aperiodic traffic is relegated to the next superframe.

In [45], the Slot Stealing MAC (SS-MAC) protocol, which was designed for star or clustering network topology is proposed. By means of this protocol, the aperiodic critical RT traffic steals the time slots assigned to non-critical traffic in order to guarantee a timely channel access of these critical transmissions.

2.3.2 MACs for industrial applications – IEEE 802.11-based solutions

Until recently, the main purpose of the IEEE 802.11 standard has been to give a solution to consumer electronic applications. However, as mentioned in Section 2.2.2, there is an increasing interest in the use of the IEEE 802.11 standard in industrial automation applications.

IEEE 802.11 [46] has a higher throughput than the existing low-energy and low-throughput IEEE 802.15-based industrial wireless communication standards discussed in Section 2.2.2. This feature is interesting for applications such as closed-loop control, in which a reduced latency is favoured instead of energy efficiency. In addition, IEEE 802.11 can be considered as the wireless counterpart of IEEE 802.3; both standards are based on the IEEE 802 project and use a similar random-access mechanism and frame format. Therefore, the ability to exchange frames coherently between the networks based on IEEE 802.3 and wireless extensions based on IEEE 802.11 allows a high degree of integration.

The IEEE 802.11 standard MAC architecture establishes two medium access mechanisms: Distributed Coordination Function (DCF) and PCF. DCF works on a CSMA/CA-based scheme, and in PCF an AP uses a polling scheme to determine which station is entitled to transmit at each moment. Currently, the PCF mechanism is deprecated, and consequently, this mechanism might be removed in a later revision of the standard [46].

Although the latest versions of IEEE 802.11 manage to provide IEEE 802.3-like throughput, a deterministic behaviour is not guaranteed because of its random access mechanism and is not therefore suitable for use in the FA applications [47]. Moreover, the RT performance and high packet rate are the key factors of those applications rather than the throughput, and IEEE 802.11 standard lacks these requirements.

So, with the aim to provide RT guarantees to IEEE 802.11, IEEE 802.11e amendment was introduced, which defines several enhancements to the MAC layer. To provide QoS capabilities in IEEE 802.11e, two new medium access mechanisms are defined: Enhanced Distributed Channel Access (EDCA) and Hybrid Coordination Function Controlled Channel Access (HCCA). EDCA is an extension of the DCF to support QoS, which defines eight different priority levels. The main difference between the mechanisms is the random time that each station should wait to transmit, which is smaller for higher priority traffic.

Despite the introduction of these mechanisms, IEEE 802.11e cannot be used in the industrial applications with strict time constraints, such as control applications. On the one hand, EDCA is still based on CSMA—not guaranteeing a deterministic behaviour—and on the other, the HCCA polling mechanism overheads the communication [48].

Finally, although IEEE 802.11ax [49] amendment includes techniques such as Orthogonal Frequency Division Multiple Access (OFDMA) and dynamic assignation of radio resources, it does not guarantee deterministic behaviour, because the assignation follows a random access procedure.

As mentioned before, other media access techniques, such as TDMA prove to be more efficient to guarantee the deterministic behaviour and a bounded latency [22]. This is because the access to the medium is not based on contention in TDMA. In TDMA, the available radio resources are divided between the devices and each device uses its own dedicated radio resource to transmit without the risk of collisions with other devices in the network.

Therefore, with the aim of providing RT guarantees along with a deterministic behaviour to IEEE 802.11, several MACs have been proposed in the literature.

In [50] Wi-Red is proposed, which focuses on exploiting the conventional acknowledgement (ACK) mechanism in order to optimize data retransmission. Thus, the transmission of unnecessary copies of the packets is avoided. Through this mechanism, as soon as an ACK is received by a node, the node that sent the ACK will also be notified. In addition to reducing network traffic, this approach improves both latencies and packet losses.

Another MAC scheme for RT applications is Det-WiFi [51]. This proposes a TDMA-based method for multi-hop industrial applications that belong to PA. Det-WiFi proposes a cyclic superframe composed of slots for sending beacons and slots to transmit and receive data in RT. The AP will be in charge of managing and sending the scheduler to all the nodes of the network. The schemes proposed in [52] and [53] have also been designed for their use in RT PA applications.

In [54], an IEEE 802.11g physical and a TDMA-based MAC layer are designed under a proposal called IsoMAC. The superframe proposed by IsoMAC implements a scheduled phase for RT traffic and a contention phase for the BE traffic. The proposed MAC scheme can fulfil a communication cycle of 4 ms at the expense of a reduced number of nodes.

In [55] three different MACs are proposed that extend the previous work proposed by the same authors in [56]. They all follow the time-triggered paradigm, in which the transmissions are predefined in a scheduler that will be followed by all the devices in the network. The proposed MAC schemes, like in TT-Ethernet, support Time-Triggered (TT), Rate-Constrained (RC) and BE traffic. These are the proposed MAC schemes (they are also represented in Figure 2.7):

1. **Pre-scheduled timeslots**: TT and RC traffic will have a specific slot allocation given by the scheduler. BE traffic will be placed in the remaining slots under a round-robin schedule, giving the same number of slots to each node.

2. **Contention-based timeslots**: similar to the first MAC scheme, except that the remaining slots will be used by BE traffic following a contention process based on slots. In each slot, a node will have the priority.

3. **Contention-based phases**: a scheduled phase is proposed for TT and RC traffic and the remaining superframe is proposed as a contention phase for the BE traffic. The advantage of having the scheduled phases distributed uniformly through the superframe is that the channel access delay is reduced for BE traffic. The drawback is that the intervals between the scheduled slots may not be large enough to accommodate the time it takes for contention and transmission.

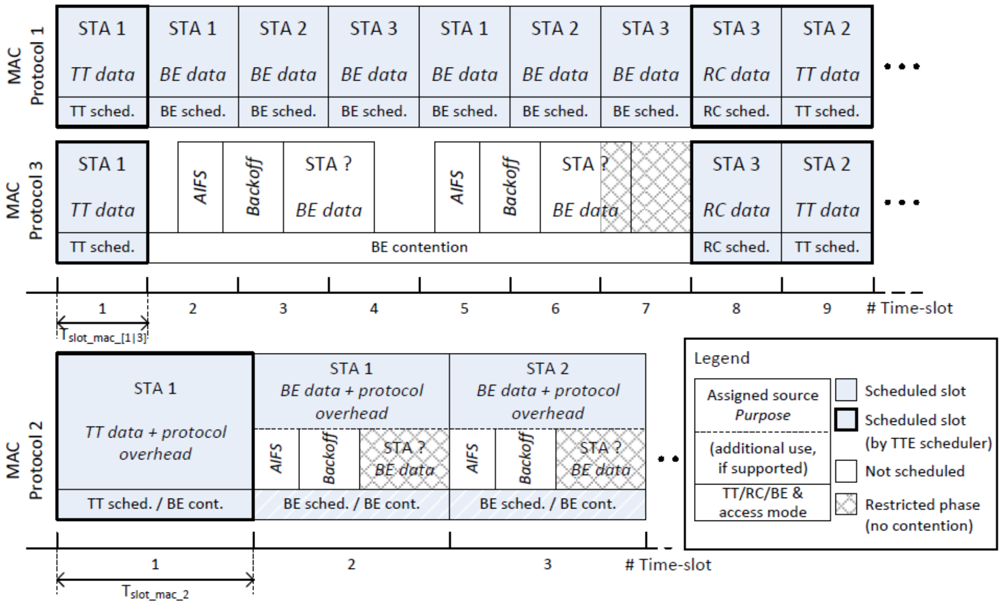


Figure 2.7: Example of slot allocation proposed in [55].

2.4 Hybrid networks

As stated previously, wireless communications offer significant benefits over wired communications. However wired communication cannot be directly replaced by wireless solutions [14] and that is why wireless communications can be seen as an extension to the existing wired networks.

There are several works in the literature that deal with issues related to hybrid networks for in industrial automation environments. The works [57]–[59] focus on the wireless extensions of existing wired industrial standards. For that, they seek to optimize the standards based on the needs of the wireless medium. It must be said that these solutions do not modify the non-deterministic medium access mechanism used by the standards, so the wireless extension maintains uncoordinated medium access. In [60], [61] the concepts of a wireless gateway for the integration of wireless transmission systems in control systems based on Industrial Ethernet are proposed. In the same way, in [62] a hybrid network architecture composed by a TSN wired network and a deterministic wireless MAC is proposed. In contrast, in [55] a MAC protocol that can be used in the wireless segment of a wired/wireless hybrid network that supports RT traffic with diverse requirements is proposed.

The integration of wired/wireless networks in industrial applications is not an easy task, because they have to provide strict reliability and time constraints to have a seamless coexistence [17]. Moreover, to achieve this, the time constraints of the application, the packet structure and the wireless communication system latency must be taken into account [60].

A clear example of a hybrid network for industrial control applications in which it is necessary to meet strict requirements in terms of time and reliability are Networked Control Systems (NCS) or DCS. As can be seen in Figure 2.8, the NCS is composed by devices such as sensors, actuators, Programmable Logic Controllers (PLC), a system to be controlled and the communication network itself to create closed control loops. NCS are control systems whose feedback loops are closed by RT networks, where information is distributed among the devices of the system through the underlying networks. Although these systems are usually implemented in wired networks, they can be extended to wireless networks, as long as a continuous coexistence between both mediums is provided. Generally, the PLC will be located on the wired segment of the network. The main reason is that due to the shared medium of the wireless network the behaviour of the PLC could be compromised with the consequent decay of the performance of the system. In contrast, the sensors and actuators that make up the NCS may be located on whatever segment (wired or wireless), thus creating a hybrid network.

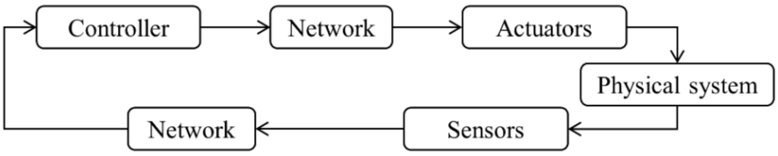


Figure 2.8: Topology of an NCS.

The task of the sensors is to obtain information from the environment, which is sent to the PLC, to process it and to make decisions accordingly. The decision taken by PLC is sent to the actuators that perform the requested task. The control cycle of the system is considered as the time interval from the reading of the sensor until the PLC output is applied by the actuator [54]. The closed-loop control applications, commonly, execute its control algorithm periodically. So, this feature must be guaranteed in the hybrid networks to ensure deterministic behaviour.

In hybrid applications, the interconnection of the different networks is reached by means of Intermediate Systems (IS). The most used IS for hybrid networks are APs, so they will be the central axis of the hybrid network. APs will act as a bridge between the wired RTE and the wireless communication system. So, the Aps will be equipped with two transmitting/receiving interfaces (one for the RTE network and one for the wireless network), and a protocol converter that allows encapsulating the packets of the wired network in packets that the wireless network can interpret and vice versa. Summarizing, the APs will receive frames from either of the two networks, then it will convert them in frames interpretable by the other network and finally, it will retransmit the frames.

2.5 Mobility in wireless networks

Since most industrial control applications have been using wired centralized networks, mobility is rarely required, so the configuration of the network is usually static. However, given the interest to control all the devices that make up industrial applications, when a wired connection is impossible due to the demand for mobility, it is indispensable to use wireless connections. Moreover, wireless networks provide more flexibility to the system. Therefore, and increasingly, mobility begins to become a requirement in industrial applications such as those that require robots/drones to transport/handle material within manufacturing plants or applications in which Autonomous Mobile Robots (AMR) are used to perform a variety of industrial tasks (e.g. a self-organizing production line) [63]. In addition, the incorporation of mobile devices allows expanding the application area and obtaining even more benefits from using wireless solutions.

Nevertheless, guaranteeing the robustness and determinism required by FA applications where mobile devices roam among the various APs located in the network is not an easy task. In these cases, the APs must synchronize and share information to maintain consistency throughout the network. It is also essential that mobile devices can change the AP transparently and without interruptions. Hence, having wireless mobile devices within a hybrid industrial network brings new challenges that must be faced, being the most critical the handover mechanism.

2.5.1 Handover mechanism

A fundamental requirement to take into account, when designing a handover mechanism, is the communication interruption during its execution. There are two ways to make a handover: i) break-before-make or hard-handover or ii) make-before-break or soft-handover. With the first, the communication between the associated AP and the node that is requiring a handover is interrupted, causing packet losses. The communication is then resumed when the handover has become effective and the node is associated with a new AP. In contrast, in the make-before-break or soft-handover algorithms, the interruption of the communication between the associated AP and the node that is requiring a handover is avoided. Hence, the most critical industrial applications require the use of make-before-break or soft-handover algorithms, where the communication is not interrupted, maintaining the connection between both APs during the execution of the handover. Note that the soft-handover algorithms achieve an uninterrupted communication through more complex algorithms and using more network resources (often even a second radio interface which increases the cost of the system), which entails an increased network overhead. Moreover, these soft-handover algorithms often require even a second radio interface, which leads to an increase in the cost of the system.

The handover mechanism used in IEEE 802.11 and in Long-Term Evolution (LTE) technology are described in the following sections.

2.5.1.1 IEEE 802.11 based handover algorithms

The handover process of the IEEE 802.11 standard consists of 3 main phases: discovery, authentication and association.

The discovery phase is, in turn, divided into triggering and scanning phases. In the triggering phase, the handover is triggered based on a previously defined criterion. At this point, the scanning phase starts, which can be either in passive or active mode. In the passive mode, the wireless device will locate the APs in its coverage range upon receiving the beacon frames sent periodically by them. On the contrary, in active mode (shown in Figure 2.9), the wireless device will transmit probe request frames on all channels and the APs in its coverage range will respond with probe response frames. The time elapsed in this probing process contributes to the majority (≈ 90%) of handoff latency [64]. In both scanning modes, information related to the neighbour APs is collected. Based on this information, the mobile device will select its target AP according to the link quality.

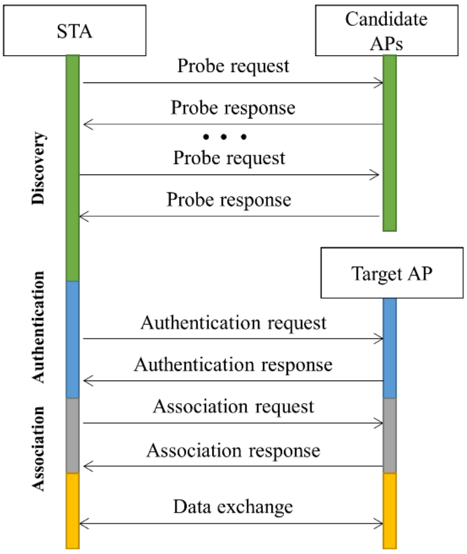


Figure 2.9: IEEE 802.11 handover process (active mode).

During the authentication phases, the device that has started the handover process will send its credential to the target AP through an authentication request. The target AP must reply with a response frame, indicating the state of authentication. The length of the authentication process depends mainly on the authentication scheme used. For the applications in which the authentication is not required (open systems scheme), there is no such delay.

Once the authentication is successfully executed, the device that has started the handover process will send an association request to the target AP, which will respond with an acceptation or rejection through an association response frame. Once the association between the device and the target AP is reached, they will be able to exchange the data packets.

During the IEEE 802.11 handover process, the device cannot exchange data frames either with the current AP or with the target AP. In the first case, the device must break the association with its AP to be able to associate with another one, and in the latter, until the association between both is confirmed, the exchange of data packets is not possible. In both cases, an interruption in the communication occurs. The duration of the interruption depends on multiple factors (channels to scan, channel switching…) and on the conditions of the environment. The interruption during Layer 2 IEEE 802.11 handover can last up to a few seconds [65].

To speed up the authentication phase during the handover process, the IEEE 802.11r amendment includes the Fast Basic Service Set Transition (FT) protocol to ensuring that the authentication processes and encryption keys are established before a handover takes place. Nevertheless, it is shown in [66] that, using the FT protocol in a network with 2 APs and one mobile device network, the interruption during the handover is still 30 ms. In [67], also using FT, they manage to further reduce the interruption during the handover to 13 ms on average, but it is only valid when a mobile device returns to an already visited AP, i.e. when a re-association is made.

In [68], a handover algorithm in which the mobile devices change AP, believing that they are simply changing the channel, is proposed. To make this possible, two IEEE 802.11 interfaces are required. The measurements made with real devices show an interruption of the communication of 130 ms. On the other hand, there are several proposals in the literature focused on reducing the duration of the scanning phase but keeping the other phases of the IEEE 802.11 handover process. For instance, the proposal in [65] focuses on optimizing the scanning phase through the use of the IEEE 802.11k amendment to collect information about the wireless medium, prior to the handover execution. By means of this mechanism, it is only necessary to scan the relevant channels. Meanwhile, a multi-beacon scheme is proposed to eliminate the scanning phase in [69], [70]. In the communication scheme proposed in [69], a beacon period is defined, in which each AP transmits beacon frames in its neighbouring APs' channels. In this way, the mobile station will receive during this period the beacons sent by all available APs in its coverage range and will decide whether to execute a handover or not. On the contrary, in [70], these beacons are not sent during a dedicated phase, being a second IEEE 802.11 interface used for that purpose. It is necessary to emphasize that none of the mentioned proposals prevents the existing communication interruption during the handover process.

In the same way, there are many handover algorithms that are based on the position of the device to reduce (not avoid) the interruption of communication during the execution of the handover [71], [72]. Finally, it is described in [73] how to avoid the communication interruption during the handover, but it is at the expense of exploiting a predictable geometry, such as the motion paths of trains.

Note that all these solutions use the non-deterministic IEEE 802.11 MAC that it is not suitable for FA applications and the evaluation of the algorithms is carried out considering a network with a reduced number of nodes.

2.5.1.2 LTE handover algorithm

Current cellular technologies, such as LTE and the upcoming Fifth Generation (5G) are considered as solutions to be used in industrial applications since they can satisfy low-latency requirements [74]–[76]. Given that cellular networks are dynamic and flexible communication networks able to adapt their configuration to changes in the environment, the handover algorithm used by LTE is analysed in order to determine if it could be used in the most critical industrial applications.

As in IEEE 802.11 standard, the handover algorithm used in the current LTE technology causes an interruption in the communication [77]. This handover mechanism is divided mainly into three phases: measurements, decision and confirmation.

In the measurement phase, the mobile device associated with a base station will constantly monitor the channel, making certain measurements, such as the power received from the neighbouring base stations, the speed of the mobile device or the impact of the interferences. Based on those measurements, the base station will take the decision to execute a handover or not.

In the decision phase, the base station will request the handover of a mobile device to another base station. To make this possible, the base station that originates the handover must indicate the target base station about the transmission resources that the mobile device requires at this point. The target base station will accept or reject the handover depending on whether it has enough resources to host the mobile device. The target base station must communicate its decision to the base station that has initiated the handover.

Finally, the confirmation phase is when the mobile device receives confirmation whether a handover is going to happen. During this procedure, the current base station must send the packets to the target base station, which was destined to the mobile device performing the handover.

Ideally, in LTE, the communication is interrupted only during the time needed to carry out the execution of the handover process itself. In practice, there are additional delays, such as processing times and propagation delays that can increase the service interruption. 3GPP (3rd Generation Partnership Project) establishes a typical execution time of the LTE handover process of 49.5 ms [78], while the International Telecommunication Union (ITU) establishes it in 27.5 ms - 60 ms [79]. In [80] the measurements made in a real scenario reveal an interruption in the communication caused by the handover process of 40 ms on average. Therefore, the LTE handover algorithm is not suitable for FA applications due to the interruption in the communication during the handover execution.

2.5.2 Mobile ad-hoc networks

When devices with mobility requirements are considered, the way in which the network is organized and managed must be taken into account, both to reduce the delay and to face the changes in the topology dynamically. In centralized networks, which are commonly used in FA applications, APs are needed to coordinate the access to the wireless medium in an orderly way. If TDMA-based communication protocols are used, in addition to guaranteeing an upper bound of the delay, packet collisions rarely happen, even in high density networks, due to a well-organized scheduler [81]. However, the need for an AP limits the flexibility of the application, introduces a single point of failure and increases the network overhead among other things. Moreover, as stated previously, if the devices roam among diverse APs, the communication protocol needs a handover algorithm to deal with AP changes.

In addition, when dimensioning the network through a TDMA scheme, the AP that is responsible for controlling the access to the medium of wireless devices, must be able to manage all wireless devices given an overload situation. That is, the AP must ensure that all devices in the wireless network can transmit their RT traffic in the same superframe without compromising the operation of the system. This, in addition to entailing an oversizing of the superframe, in most of the cases because not all the devices are going to communicate with a single AP, involves high control cycles as the number of wireless devices with RT traffic increases.

In order to overcome the former challenges, in distributed networks or ad-hoc networks, the nodes communicate with each other without relying on a centralized AP. In these networks, the nodes themselves are responsible for managing the access to the medium and face the changes in the topology dynamically, i.e., nodes entering and leaving the network. Several ad-hoc MAC protocols have been proposed in the literature that are suited to industrial applications.

In [82] the token-based EchoRing protocol for decentralized architecture is proposed. Using a cooperative protocol allows selecting dynamically another station to help in the transmission process by increasing the delivery rates of packets. The cooperative station must retransmit the packet in case ACK is not received. On the other hand, if the token is lost in the retransmission process, each station will be allowed to recreate the token. This prevents the loss of the RT capabilities of non-involved stations. In this way, the next station in the ring will create a new token and refresh the old ring by the new one. This new ring will be transparent for the stations that receive from or listen to a subsequent token associated with the new ring. This protocol can be used in industrial environments with time constraints, achieving latencies of less than 10 ms.

In [83] the decentralized SchedWiFi protocol is proposed which modifies the IEEE 802.11 standard EDCA mechanism to transmit high priority scheduled traffic without requiring a predefined superframe structure or slots. In addition, the transmission of no scheduled traffic is allowed as long as it does not interfere with the scheduled one. This is possible through the introduction of the Scheduled Traffic (ST) window concept, which represents the time window in which the scheduled traffic is transmitted and the use of a Time-Aware Shaper (TAS). The TAS is in charge of blocking all transmissions that could interfere with ST windows. It is a concept similar to the one proposed by TSN.

In [84], the Ad-hoc Reconfigurable and Adaptive TDMA (RA-TDMA+) protocol is proposed for a fully distributed scenario which applies a global synchronization extending the basic mechanism proposed by Reconfigurable and Adaptive TDMA (RA-TDMA) in [85]. RA-TDMA+ considers a control cycle divided into consecutive slots of the same duration and each of the slots will be assigned to a node within a set of nodes. As the number of nodes in the set increases, the duration of the slot decreases. At the start of each slot, the node to which that slot corresponds will send a packet that contains information such as its view of the network topology or information related to the node set. After this first packet, the rest of the slot will be available for transmitting RT traffic. When a node receives this information, it will update its view of the network topology. In this way, it can determine if there have been changes in the topology and reconfigure the frame accordingly.

2.5.3 *Vehicular communications*

Vehicular ad-hoc networks (VANETs) are special cases of mobile ad-hoc networks composed by vehicles that communicate among them using wireless technologies. As in industrial applications, reliability and latency are indispensable requirements of these networks together with the mobility of the nodes. However, the requirements in terms of reliability and determinism tend to be less restrictive than in FA applications [10].

For example, road safety vehicular applications, which include warning other road devices about collisions or dangerous situations, require an end-to-end delay in the range of 10 ms – 100 ms and PLRs at application level from 10^{-3} to 10^{-5} [10]. In addition, the update time is 100 ms, communication ranges of up 500 m are considered and the devices can move at maximum speeds of 100 km/h and 500 km/h in urban and highway scenarios, respectively. Moreover, a large number of devices are considered (3000 vehicles/km^2 in urban areas and 500 vehicles/km^2 in highway scenarios). In safety vehicular applications, the transmitted traffic is periodic and packets of up to 500 bytes are sent.

In contrast, as mentioned before in Section 2.1, FA applications such as closed-loop control or mobile robots require an end-to-end delay below 1ms, PLRs at application level from 10^{-6} to 10^{-12} and a maximum jitter of 1 ms. In addition, the cycle time of the system is in the range of 50 µs – 1 ms, the coverage area varies between 10 – 100 meters and the devices can move at a maximum speed of 30 km/h. Moreover, these applications do not require a large number of devices (10 – 100 devices) and the amount of data to be sent per packet is reduced (15 – 64 bytes) [1], [2], [9], [10].

The main communications in VANETs can either be between vehicles and Roadside Units (RSU) (Vehicle-to-infrastructure – V2I) or between vehicles (Vehicle-to-vehicle – V2V). In V2I, RSUs are needed as an AP to connect vehicles to the network infrastructure, whereas in V2V the vehicles can communicate with each other in an ad-hoc way. The V2I communication protocols are out of the scope of this research because decentralized protocols are sought as an alternative to carrying out a handover without centralized systems. Note that for the considered application, the desired decentralized MAC scheme must to provide an efficient mechanism to share the bandwidth resources fairly, ensure a reduced jitter and delay and guarantee a reliable communication.

The used physical and MAC layers in vehicular communication are specified by the IEEE 802.11p standard. In the MAC layer, the traffic classes differentiation is achieved through the EDCA mechanism (inherited from the IEEE 802.11e amendment). Besides that, the IEEE 1609 protocol suite is included, that provided, among others, multichannel operation in DSRC (Dedicated Short-Range Communications) band (also called ITS-G5 in Europe), resource manager and security services. The combination of IEEE 802.11p and the IEEE 1609 is known as Wireless Access in Vehicular Environments (WAVE) [86].

Note that, since the MAC used in IEEE 802.11p is based on contention, it does not guarantee a deterministic behaviour. In order to solve this, several distributed MAC protocols have been proposed in the literature for use in VANETs. In [87], the TDMA-based MAC protocol VeMAC is proposed. In VeMAC, disjoint sets of slots are assigned to vehicles moving in opposite directions, as well as to RSUs, and it can be used to transmit both one-hop and multi-hop broadcast packets. The assignment of time slots is performed in a centralized way by a certain vehicle denoted as provider.

In CFR MAC [88], the superframe is created based on the speed of each vehicle and the direction in which they are moving. The slots assigned for each speed and direction will be adjusted dynamically.

In STDMA [89], when a vehicle joins the network, it must first listen to the medium to get information related to slot assignment of the other vehicles. It will choose one among the slots detected as free and will occupy it in the next superframe. The selected slot will be assigned to the vehicle for a determined period, after which a slot reassignment must be performed.

In [90], the TDMA-based DTMAC protocol is proposed, which is based on VeMAC. Unlike in VeMAC, DTMAC allows parallel transmissions in different areas. To make this possible, the protocol divides the road into areas and allows using the same slot by multiple vehicles as long as they are not in nearby areas.

In [91], [92] an enhanced version of the previously described RA-TDMA protocol is proposed. In this MAC scheme a position-based admission control is included to the original RA-TDMA protocol in order to coordinate the transmission of the packets of the different vehicle sets. As in RA-TDMA, the proposed scheme supports asynchronous packets transmissions using the CSMA/CA protocol inherent in IEEE 802.11p MAC layer.

A Dynamic Token-Based MAC (DTB-MAC) protocol is proposed in [93] in order to prevent channel contention as much as possible in IEEE 802.11p MAC layer. With the proposed scheme, the vehicle holding the token transmits its periodic beacon and selects another vehicle in the same ring as the next token holder. The token holder selection mechanism takes into account the beacon delivery deadlines of the neighbouring vehicles in order to select the one with the nearest deadline. An extension of this protocol is presented in [94] to incorporate mechanisms to handle the transmission of event-driven packets.

Moreover, current cellular technologies, such as LTE, can also be used in vehicular communications. The Release 14 [95] of the LTE includes support for V2V communications and a mode (mode 4) where vehicles autonomously select and manage the radio resources without any infrastructure support. For that, a sensing based Semi-Persistent Scheduling (SPS) is proposed whose objective is to improve the reliability of the communication without overloading the channel with retransmissions.

2.6 Chapter summary

This chapter summarizes the background and related work on wired and wireless industrial communications. Moreover, the requirements and the challenges of the industrial applications are presented. The existing standards for industrial application in both wired and wireless domain have also been detailed.

The inability of the wireless standards to ensure the requirements of the most critical industrial applications has led to new proposals, which have been delved in this chapter. Then, a general analysis of the state-of-the-art related to hybrid networks is provided. Finally, an analysis of the industrial wireless networks with mobility requirements in both centralized and decentralised topologies is made. For that, first, several handover mechanism proposals are detailed. Second, mobile ad-hoc networks are defined as well as some ad-hoc MAC protocols that are suited to industrial applications are described. Finally, vehicular communications are detailed given that they are a special case of mobile ad-hoc networks composed by vehicles. Along with the definition of vehicular networks, the standards communications protocols used in these networks are provided, as well as, several MAC protocols designed for vehicular communications.

Chapter 3

Deterministic MAC scheme for hybrid Distributed Control Systems

One of the main objectives of this thesis is to propose a hybrid RT communication scheme for FA applications. Therefore, in this chapter, a hybrid wired/wireless RT MAC scheme is proposed. This MAC scheme focuses on guaranteeing the robustness and determinism required by the closed-loop control applications, besides from expanding the wired network used in those applications to a wireless domain. The first section of this chapter describes the architecture of the proposed hybrid network as well as the MAC schemes proposed for both the wireless and wired segments. In Section 3.2 a theoretical analysis is made to determine the delay bounds of the proposed wireless part of the hybrid MAC scheme. Moreover, the simulation setup and the obtained OMNeT++ results are also presented in Section 3.2.

3.1 Proposed hybrid RT MAC scheme

As stated in Chapter 2, current wireless standards do not allow the coexistence with wired networks that present strict reliability and RT requirements, such as in FA applications. In order to solve this issue, a hybrid RT MAC scheme that guarantees a deterministic communication is presented.

The hybrid RT MAC scheme has been proposed for scenarios with strict requirements in terms of robustness, determinism and RT within a hybrid network architecture. The considered network architecture, shown in Figure 3.1, comprises a network controller (a PLC), APs connected to the wired network to cover the wireless area and sensors and actuators distributed along the hybrid network (named nodes or devices indistinctly). The PLC will be placed in the wired segment to avoid compromising the process with the performance degradation due to the shared medium of the wireless network. On the other hand, to guarantee the requirements needed by the control applications, the proposed hybrid architecture will follow a tree topology, which offers both high performance and high scalability. If we focus on the wireless segment, a star topology is proposed. In the closed-loop control applications, where the control cycle period is low, a reduced latency is sought and the star network is more suitable because the wireless coordinator (the AP in this case) schedules RT packets in a more restrictive way [14].

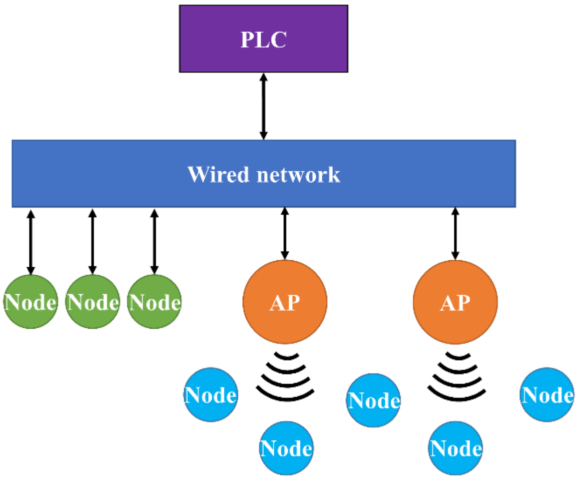


Figure 3.1: Proposed hybrid network topology.

In this architecture, the AP will act as a bridge between both media—routing the packets from the wired network to the wireless network and vice versa and will coordinate the access to the wireless medium through the proposed TDMA-based MAC respecting the control cycle of the system. The control cycle of the system is defined as the time interval from the moment the sensor is read until the PLC output is applied by the actuator [54].

To control the wired network, an RTE based MAC scheme is proposed. This MAC must provide a timeslot whenever the AP requires performing an uplink (from the AP to the PLC) or downlink (from the PLC to the AP) transmission. Thus, synchronization between the two networks is achieved.

As stated previously, the proposed hybrid RT MAC schemes allow the coexistence of three traffic types: periodic RT traffic, aperiodic RT traffic and BE traffic. With a predictable arrival pattern, the periodic RT traffic corresponds to data transmissions of the read and write operations of the sensors and actuators. These data flows from the nodes distributed along the hybrid network to the PLC and vice versa. That kind of traffic will be generated periodically (taking into account the control cycle of the system) in a determined time instant in all the devices of the network. In contrast, the aperiodic RT traffic, with an unpredictable arrival pattern, corresponds to those data flow transmissions such as alarms that are sent to the PLC. Since the transmission rate of the aperiodic traffic is much lower than the periodic data, just one possible aperiodic flow will be considered in each segment of the hybrid network within a control cycle. Finally, BE traffic corresponds to those data flows that are not sensitive to QoS metrics.

3.1.1 Proposed wireless medium access

To control the shared medium of the wireless extension in a deterministic way, a cyclic TDMA-based MAC is proposed that is based on the IEEE 802.11 physical layer. We use an IEEE 802.11 physical layer due to the increasing interest in the use of this standard in industrial applications [96]. The proposed TDMA-based MAC scheme sub-divides time into consecutive superframes and each superframe is, in turn, subdivided into a variable number of time slots. The definition of the proposed MAC scheme is based on the superframe of IsoMAC [54] described in Chapter 2.

The proposed wireless superframe, as shown in Figure 3.2, is divided into two communication periods: one dedicated mainly to transmit/receive the pre-defined periodic RT data packets and another one dedicated to transmitting the BE information using the legacy IEEE 802.11 MAC.

3.1.1.1 Real-Time (RT) period

The RT period is based on a dynamic scheduler that will be modified only when a node is associated/dissociated with the AP. The AP is the responsible of calculating and distributing the scheduler that will follow the nodes under its coverage area. This scheduler includes the transmissions instant of every RT data packets and ACKs. While a node is associated with the AP, the slots assigned to it will be non-transferable and may not be shared with other nodes. As shown in Figure 3.2, the RT period divides the superframe into multiple slots which are described in the following. Note that there is a Short Interframe Space (SIFS) interval between the slots to guarantee that the periodic RT traffic has a higher priority against the legacy BE IEEE 802.11 traffic.

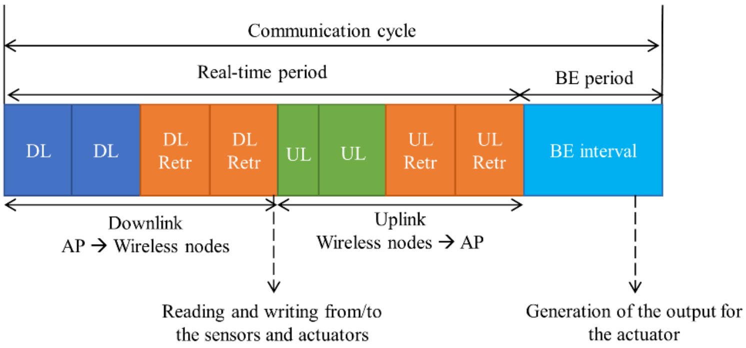


Figure 3.2: Proposed wireless MAC superframe structure.

1) Downlink (DL) slots

Periodic RT data packets transmitted from the AP to the nodes are transmitted during those slots. Each node associated to an AP will have assigned a slot to receive, through the AP, the periodic RT traffic sent by the PLC (DL slot).

As shown in Figure 3.2, when the DL retransmission slots ends, the value of the actuators (both wired and wireless) must be updated and the new state of the sensor (both wired and wireless) must be read. Thus, the wireless superframe must schedule the DL phase before the UL phase in order to synchronize with the reception of the periodic RT traffic sent by the PLC.

In order to increase the reliability of the wireless system, once the AP transmits the DL packet, the node must respond it with an ACK if the reception of the RT packet is correct, and with a negative acknowledgment (NACK) if they do not receive the expected DL packet or if the reception is incorrect. Whether the AP receives a NACK or does not receive any response from the node to which the packet sent in the DL slot was addressed, the DL packet will be saved in a queue for its retransmission in the DL retransmission slots.

2) Downlink retransmission (DLRetr) slots

The main task of those slots is to retransmit the periodic RT data packets of the DL period.

All transmissions made in the DLRetr slots must be acknowledged. During the DLRetr slots, the AP will retransmit the packets based on the retransmission queue. So, the first packet in the queue will be the first to be retransmitted.

In the case of DLRetr slots will be left unused, they can be used for other purposes such as to send BE traffic or to send changes in the scheduler due to a handover.

3) Uplink (UL) slots

Periodic RT data packets transmitted from the nodes to the AP are transmitted during those slots. Each node associated to an AP will have assigned a slot to transmit periodic RT traffic to the PLC (UL slot).

As shown in Figure 3.2, before transmitting UL data packets, the value of the actuators (both wired and wireless) must be updated and the new state of the sensor (both wired and wireless) must be read.

Unlike in DL slots, only the last UL slot must be acknowledged. Therefore, the duration of the UL slots (except the last one which has the same duration as the DL slots) is shorter than DL slots. Despite no acknowledged, the AP will keep track of the messages it has received on those UL slots. The AP will use the information of the scheduler to know which nodes have sent the successfully received UL data packets. This information will be broadcasted by the AP to all wireless nodes in the network as a response to the RT data packets sent by a node during the last UL slot.

If the wireless nodes receive the broadcasted information packet, it will check if the AP has received the UL RT data packet sent by them. If this information ensures that the sent UL RT data packet has not been received correctly, the node will save the previously sent UL packet in a queue for its retransmission in the UL retransmission slots. In the same way, if a node does not receive the broadcasted information packet, it will also save the UL RT data packet for its retransmission just in case.

4) Uplink retransmission (ULRetr) slots

The main task of those slots is to retransmit the periodic RT data packets of the UL period.

All transmissions made in the ULRetr slots must be acknowledged. Moreover, the retransmissions must be done in an orderly fashion in order to prevent several nodes from retransmitting at the same time. In order to do so, priorities will be established. These priorities will be assigned by the AP when defining the scheduler. Note that a node that has been newly associated with an AP will be assigned a priority that is not being used by any neighbouring node associated with this AP. Thus, if a wireless node has a UL RT data packet to retransmit, it will wait for a short period (t_{ret}) defined based on its priority as stated in (3.1). This time interval will correspond to the maximum propagation delay (t_{prop}) of the network. The node with the greatest priority ($p = 0$) will have the right to retransmit immediately without having to wait.

$$t_{ret} = p \cdot t_{prop}. \tag{3.1}$$

If the channel remains idle after this time interval, it means that no wireless node with higher priority has tried to retransmit; so, the UL retransmission is possible. Once the UL retransmission slot ends, the node that has retransmitted will have the lowest priority and the others will increment their priority by one.

Finally, if the ULRetr slots will be left unused in a control cycle, they can be used to send BE traffic or to send changes in the scheduler due to a handover. In the case of scheduler changes, the device should wait for a predefined time interval greater than the maximum t_{ret} that a wireless node that wants to retransmit periodic UL traffic can wait. In this way, the transmission of the scheduler changes is prevented from colliding with periodic RT traffic retransmission made from another node.

3.1.1.2 BE period

This period is used to transmit by contention the BE packets using the legacy IEEE 802.11 MAC.

Note that the AP must access to the medium some microseconds before the BE period ends in order to ensure that no other node begins to transmit a BE packet prolonging the contention period (BE interval). This method, proposed in [19], prevents any BE packet from invading the RT period.

3.1.1.3 Duration of the slots of the RT period

The DL (t_{DL}) slots, DL Retr (t_{DLRetr}) slots, UL Retr (t_{ULRetr}) slots and the last UL (t_{lastUL}) slot will have the same duration, which is equivalent to:

$$t_{DL} = t_{DLRetr} = t_{ULRetr} = t_{lastUL} = t_{data} + t_{ACK} + t_{prop}, \tag{3.2}$$

where t_{data} defines the duration of a data frame and t_{ACK} defines the duration of an ACK/NACK frame and are defined as follows:

$$t_{data} \text{ or } t_{ACK} = t_{preamb} + t_{signal} + \left\lceil \frac{N_B + N_{SB} + N_{PB}}{N_{DBPS}} \right\rceil \cdot t_{OFDM_{Symb}}, \tag{3.3}$$

where $t_{preamb}$is the preamble duration, t_{signal} is the signal symbol duration and $t_{OFDM_{Symb}}$ is an Orthogonal Frequency Division Multiplexing (OFDM) symbol duration. Moreover, N_B is the number of bits in the payload, N_{SB} defines the 16 bits added before the payload, N_{PB} indicates the 6 bits added after the payload and N_{DBPS} is the number of bits in an OFDM symbol. Finally, $\lceil \cdot \rceil$ is the operator ceil, which rounds up the value.

On the other hand, the UL ($t_{notLastUL}$) slots (except the last one) will have a duration equivalent to:

$$t_{notLastUL} = t_{data} + t_{prop}. \tag{3.4}$$

3.1.1.4 Dynamic scheduler

The proposed MAC scheme must be combined with a dynamic scheduler to cope with the changes in the network.

Note that the control cycle of the system remains invariant, as well as the duration of the defined wireless superframe—the number of UL and DL slots in the superframe will vary depending on the number of the associated devices in each AP.

In addition, on the one hand, the duration of the DL interval (DL slots + DLRetr slots) must always be the same regardless of the number of associated devices because, at the end of the DL interval, all devices (wired and wireless) update the actuator value and read the new status of the sensor at the end of the DL interval. The unused DL slots will be used for retransmissions. Note that a minimum of slots dedicated to DL retransmissions must always be guaranteed.

On the other hand, the duration of the UL interval (UL slots + ULRetr slots), is variable. Since a minimum BE interval must be guaranteed within a wireless superframe, the rest of the superframe duration can be used for the UL transmission, again guaranteeing a minimum of slots dedicated to UL retransmissions. If more time is available but is not enough for a new UL retransmission slot, this is going to be added to the BE interval.

3.1.2 Proposed wired medium access

To control the wired network, an RTE or TSN based MAC scheme is proposed. In both cases, a timeslot must be provided every time the AP requires performing an uplink (from the AP to the PLC) or downlink (from the PLC to the AP) transmission.

3.1.2.1 Proposed RTE MAC scheme

Taking as a reference the MAC scheme proposed for the wireless segment, another TDMA-based cyclic MAC is proposed to control the wired segment of the closed-loop control application. This MAC will be similar to the one proposed for the wireless segment. The major difference between them is that, as the wired network is a controlled medium, it does not require time slots for retransmissions since packet reception fails so little that its recovery is delegated to upper layers. On the other hand, it is necessary to take into account that being a hybrid network, it is necessary to provide a superframe structure that synchronizes perfectly with the superframe used to control the wireless segment.

For this purpose, the superframe structure shown in Figure 3.3 is proposed. In the proposed superframe, if the wired devices or the AP must send periodic traffic, the assigned slots will be UL. In contrast, if the PLC must send periodic traffic to the devices, the assigned slots will be DL. Taking this into account, there will be one UL and one DL slot per device in the network. As in the wireless segment, to synchronize with the reception of the data resulting from the wireless network, the DL slots must be scheduled before UL slots. Moreover, and as stated previously, this MAC must provide a timeslot whenever the AP requires performing an uplink or downlink transmission.

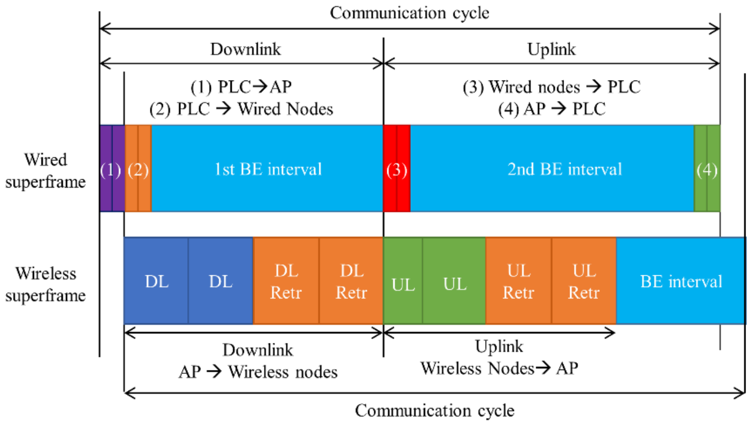


Figure 3.3: Integration of the proposed wireless and wired MACs.

At the end of the downlink interval, all devices (wired and wireless) update the actuator value and read the new status of the sensor. Taking this into account, the start of the first UL slot will be perfectly synchronized with the first UL slot of the wireless network superframe. On the other hand, at the end of the uplink interval of the wired superframe, the PLC calculates the output for the actuators based on the received readings of the sensors. Therefore, for the PLC to process and send this information properly to all devices in the network, a small offset is required between the first DL slot of the wired and wireless superframe. The reason for this is that within the hybrid network, first the actuator output must be sent from the PLC to the AP, and then from the AP to the corresponding wireless device. For the same reason, the UL slots assigned to the AP will go after the UL slots assigned to the wired devices. The possible retransmissions of the UL traffic in the wireless segment must be received by the AP before the beginning of the UL slots assigned to this one. All the UL and DL slots will have the same duration in the wired superframe.

Besides, to get synchronization between wired and wireless superframe, and also to support aperiodic RT traffic or BE traffic, the addition of two-time intervals is proposed. The first BE time interval will be placed between the assigned wired nodes to PLC slots and the assigned AP to PLC slots. On the contrary, the second BE interval will be placed between the assigned devices to PLC slots and the assigned AP to PLC slots. It would also be possible to place the BE interval at the end of the all slots allocated for UL traffic but in this case, the MAC scheme would not be compatible with the handover mechanism described in Chapter 4. These BE intervals will make it possible to transmit aperiodic or BE traffic and changes in the scheduler.

Finally, as in the proposed wireless MAC scheme, the defined wired MAC scheme must be combined with a dynamic scheduler to cope with changes in the network.

3.1.2.2 Integration with TSN network

The proposed wired RTE-based MAC scheme can be replaced by an RTE wired standard. Among the existing wired RTE protocols able to fulfilling the strict requirements of FA applications, TSN [19] technology has been selected to replace the proposed RTE wired proprietary solution. TSN is a set of IEEE 802 sub-standards with the objective of providing deterministic communication with RT guarantees over Ethernet by using time synchronization and a scheduling information which is shared between all the devices of the network through TSN switches.

The expected use of TSN in future automation systems and the similarities of the TSN's traffic scheduler with the proposed wireless MAC scheme, allows a high degree of integration between both schemes. Moreover, some of the concepts considered by TSN can be brought to wireless networks [97], so that the wireless segment could be seen as an extension of TSN.

The core of TSN is the IEEE 802.1Qbv [98] sub-standard which is responsible of scheduling the traffic in a deterministic way. The existing prioritization mechanisms in Ethernet do not guarantee a predictable delivery time. So, to solve this, IEEE 802.1Qbv proposes to divide the Ethernet traffic into different classes based on their priorities. The switched networks will be responsible for scheduling this traffic in a deterministic way through different queues. This concept is called Time-Aware Shaper (TAS) in TSN and it uses the principle of time-triggered communication. This mechanism permits a defined time window, in which the transmission of the most critical frames are foreseen without being interfered by other less critical transmissions. To make this possible, each Ethernet frame will be assigned to a queue based on its priority. Queues have been previously defined within a schedule, and the transmission of packets will be sent during the scheduled time window. During these time windows, queues that are not transmitting will be blocked to ensure that non-scheduled traffic is transmitted. In order to block the queues, transmission gates concept is introduced. These gates are used to enable separate transmission queues and they can be open or closed. The state of the gates is defined within a schedule and the TAS opens and closes the transmission gate at specific times. At the time of choosing the next message to be transmitted, messages from those queues whose gates are open may be selected. The TSN switches will be in charge of controlling that the gates are opened at the scheduled time in order to guarantee the low latencies required in the network.

Taking this into account, the mechanism proposed by IEEE 802.1Qbv will be in charge of controlling the wired medium access within the proposed hybrid architecture. The defined time windows used to transmit the RT packets must be scheduled in such a way that a perfect synchronization with the previously defined wireless MAC scheme can be achieved as seen in Figure 3.4. This concept is the same as that considered in the proposed RTE wired MAC scheme in Section 3.1.2.1.

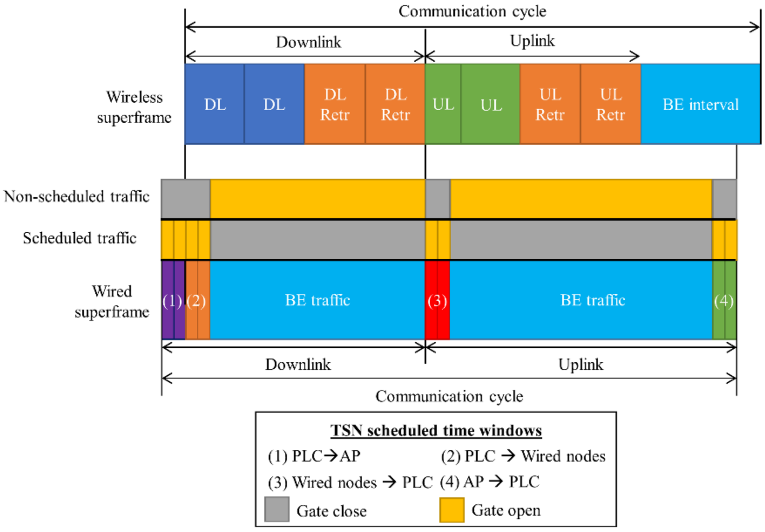


Figure 3.4: Integration of the proposed wireless MAC and TSN.

In order to achieve the mentioned synchronization, the scheduled time window dedicated to transmitting RT data packets between the PLC and the AP must be defined before the beginning of the DL slots of the wireless superframe. The reason for this is that the AP needs to have received the RT data packets from the PLC before sending them to the wireless medium. In the same way, the AP needs to have received the RT data packets transmitted from the wireless medium before sending them to the PLC. That is why, the scheduled time window dedicated to transmitting RT data packets between the AP and the PLC must be defined after the ending of the UL slots of the wireless superframe.

The remaining time interval left by the scheduled time window, within the wired superframe, will be used for the transmission of aperiodic or BE traffic and also to send changes in the scheduler. These packets will have lower priority than the RT packets, so they will not interfere with the transmission of RT packets during the scheduled time windows. In Figure 3.4, the state of the gates that controls the transmission of the periodic RT data packets and the non-scheduled (BE traffic) traffic is shown. Taking all these considerations into account, the proposed wireless RT MAC can be seen as a wireless extension of TSN.

3.2 Performance evaluation

3.2.1 *Theoretical analysis*

A theoretical analysis has been carried out to study the validity of the proposed wireless MAC scheme described previously. The analysis has been made using Network Calculus [99]. This analytical method provides the theoretical upper bounds for the delay of periodic traffic and is especially suitable for TDMA-based MAC schemes as stated in [100], [101].

3.2.1.1 Network Calculus

Network Calculus establishes the theoretical delay and backlog bounds, considering both the input traffic and the traffic that the network can handle. The backlog is considered as the amount of data contained within the node in a determined time, i.e. the number of queued packets. These limits are necessary in RT networks in which deterministic guarantees are required. To obtain these limits, Network Calculus uses the min-plus algebra. The main difference between the classical algebra and the min-plus algebra is that the sum operator used in the former becomes the computation of the minimum (defined also as the infimum operator (*inf*) and the multiplication becomes the addition. Moreover, Network Calculus characterizes the traffic arrival by the arrival curve (α) and the availability of the network by the service curve (β). From these curves, it is possible to derive the theoretical limits of the worst case in terms of delay and backlog.

In Network Calculus, a data flow is represented by wide-sense increasing cumulative function $R(t)$. This function represents the number of bits generated during the time interval [0, t]. In the initial state, 0 bits are considered $(R(t) = 0 \ \forall t \leq 0)$. Taking all this into account, the wide-sense increasing α function is the arrival curve for a data flow $R(t)$, if:

$$R(t) - R(s) \leq \alpha\,(t - s), \qquad \forall s, t \in R;\ t \geq 0;\ \forall s \leq t. \tag{3.5}$$

This means that the data flow is limited by $\alpha(t)$ on any instant t. Furthermore, if $R(t)$ and $R^*(t)$ are considered as the input and output data flows of a node, the node offers to the data flow a service curve β, if and only if β is wide sense increasing, $\beta(0) = 0$, and if:

$$R^*(t) \geq R \otimes \beta. \tag{3.6}$$

The $\otimes$ operator represents a min-plus convolution, which is defined in Network Calculus as:

$$(R \otimes \beta)(t) = \inf_{0 \leq s \leq t} \{R(s) + \beta(t-s)\}, \tag{3.7}$$

where *inf* corresponds to the infimum operator. Taking (3.8) into account, it can be determined that $R^*(t)$ is at least the service curve β.

Once the arrival and service curves have been defined, it is possible to derive the theoretical limits of the worst case in terms of delay and backlog. The demonstration of the bounds defined below can be found in [99].

On the one hand, the backlog can be defined as:

$$x(t) = R - R^*(t). \tag{3.8}$$

Assuming an input data flow constrained by the arrival curve that crosses a network with a service curve, the backlog is bounded by:

$$x(t) \leq \sup_{s \geq 0} \{\alpha(s) - \beta(s)\}, \tag{3.9}$$

where *sup* corresponds to the supremum operator. On the other hand, the delay ($\delta(t)$) is bounded by:

$$\delta(t) \leq \sup_{t \geq 0} \{\inf \{\tau \geq 0 : \alpha(s) \leq \beta(s + \tau)\}\}, \quad \tau \in R. \tag{3.10}$$

The backlog and delay bounds can be defined more intuitively representing the arrival and service curves graphically. The Network Calculus theory stated that the backlog is limited by the vertical deviation (v) between the arrival curve and service curve, while the horizontal deviation (h) limits the delay bounds. This is reflected both in Figure 3.5 and in the following equations:

$$x(t) = v(\alpha, \beta). \tag{3.11}$$

$$\delta(t) = h(\alpha, \beta). \tag{3.12}$$

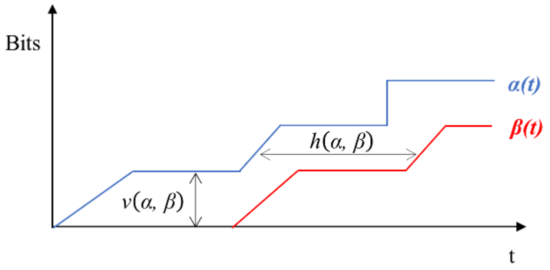


Figure 3.5: Graphical representation of the backlog and delay bounds.

3.2.1.2 Analysis of the proposed wireless MAC scheme

Since there is no backlog requirement in control industrial applications, the analysis will focus only on the delay bounds, which allow knowing whether time requirements can be guaranteed or not with the proposed wireless MAC scheme. In addition, in the following analysis, the delays introduced by the wired RT network and PLC are considered null because that they supposed fast enough, so it is transparent to the wireless network.

When calculating the arrival and service curves, the format of the proposed superframe must be taken into account to determine the RT data flow that can be guaranteed through the proposed wireless MAC scheme. Taking into account the proposed wireless TDMA scheme in Section 3.1.1, the total length of the proposed superframe (c) is:

$$c = t_{RT} + t_{BE}, \tag{3.13}$$

where t_{RT} is the time interval dedicated mainly to transmit and receive the pre-scheduled RT frames and t_{BE} is the time interval dedicated to transmitting the BE information by contention. Both $\mathrm{t_{RT}}$ and t_{BE} will have a variable value, but the duration of the superframe will always be the same (the length of the superframe must be dimensioned so that an AP can control the access to the wireless medium of a maximum number of devices at a given time, without compromising the operation of the system). As for the case of the $\mathrm{t_{RT}}$, this variability will be given, on the one hand, by the number of wireless nodes associated with each AP, and on the other hand, by the number of retransmission slots (both DL and UL) required in each superframe. In addition, the duration of the DL interval (DL slots + DLRetr slots) must always be the same regardless of the number of associated devices. The unused DL slots will be used for retransmissions. In contrast, the duration of the UL interval (UL slots + ULRetr slots) will be variable, as stated in Section 3.1.1. So, t_{RT} can be defined as:

$$t_{RT} = t_{DL} + t_{DLRetr} + t_{UL} + t_{ULRetr}, \tag{3.14}$$

where t_{DL} is the time needed to transmit the DL frames of all the nodes associated with an AP, t_{DLRetr} represents the time interval dedicated to the DL retransmissions, t_{UL} is the time needed to transmit the UL frames of all the nodes associated with an AP and t_{ULRetr} defines the time interval dedicated to the UL retransmissions. During each frame, each node can transmit/receive both in the UL/DL slot, assigned in the time interval dedicated to the retransmissions (whenever possible). Taking this into account and given that the frames in the closed-loop control applications are periodically generated, the uplink arrival curve ($\alpha_{UL}(t)$) and the downlink arrival curve ($\alpha_{DL}(t)$) of the proposed scheme are defined as:

$$\alpha_{UL}(t)=L\left\lceil\frac{t}{T}\right\rceil, \tag{3.15}$$

$$\alpha_{DL}(t)=L\left\lceil\frac{t - Offset_{DL}}{T}\right\rceil, \tag{3.16}$$

$$Offset_{DL}(t)= \ t_{UL} + t_{ULRetr} + t_{BE} , \tag{3.17}$$

$$Offset_{UL}(t)=t_{DL}+ t_{DLRetr} , \tag{3.18}$$

where T is the RT packet period, L the length of the RT and $Offset_{DL}$ and $Offset_{UL}$ are the offsets between the generation of the DL and UL traffic, respectively.

On the other hand, both the uplink ($\beta_{UL}(t)$) and the downlink ($\beta_{DL}(t)$) service curves, can be different depending on whether a node will be able to retransmit in the interval dedicated to the retransmissions. The cases shown in Table 3.1 have been considered in this analysis.

Table 3.1: Analyzed retransmission cases.

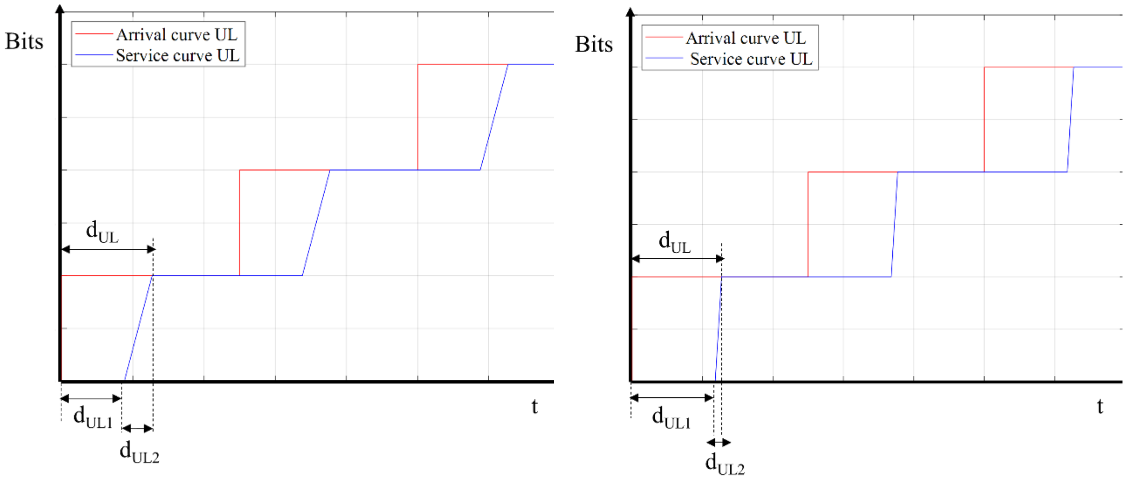
Case	Description
1	Only one node needs to retransmit both DL/UL traffic and it has the whole-time interval dedicated to the retransmission (t_{DLRetr} and t_{ULRetr} slots) to do it.
2	Only one node needs to retransmit both DL/UL traffic and it has the whole-time interval dedicated to DL retransmission (t_{DLRetr} slots) to do it.
3	Only one node needs to retransmit both DL/UL traffic and it has the whole-time interval dedicated to UL retransmission (t_{ULRetr} slots) to do it.
4	The node cannot make retransmissions neither in t_{DLRetr} nor in t_{ULRetr} slots.

To simplify the calculations, from now on, it will be considered that all the slots will have the same length. Taking this into account, the arrival and the service curves of both uplink ($\beta_{UL}(t)$) and downlink ($\beta_{DL}(t)$) and the delay obtained in each of the considered cases are shown in Table 3.2. The obtained delay is divided into the measured total UL delay (d_{UL}) and the DL delay (d_{DL}). The d_{UL} is, in turn, divided into the time interval in which the node cannot transmit in UL (d_{UL1}) and in which the node can transmit in UL (d_{UL2}). On the contrary, d_{DL} is, in turn, divided into the time interval in which the node cannot transmit in DL (d_{DL1}) and in which the node can transmit in DL (d_{DL2}). Finally, B represents the transmission capacity of the link.

Table 3.2: Obtained service curves and delay equations.

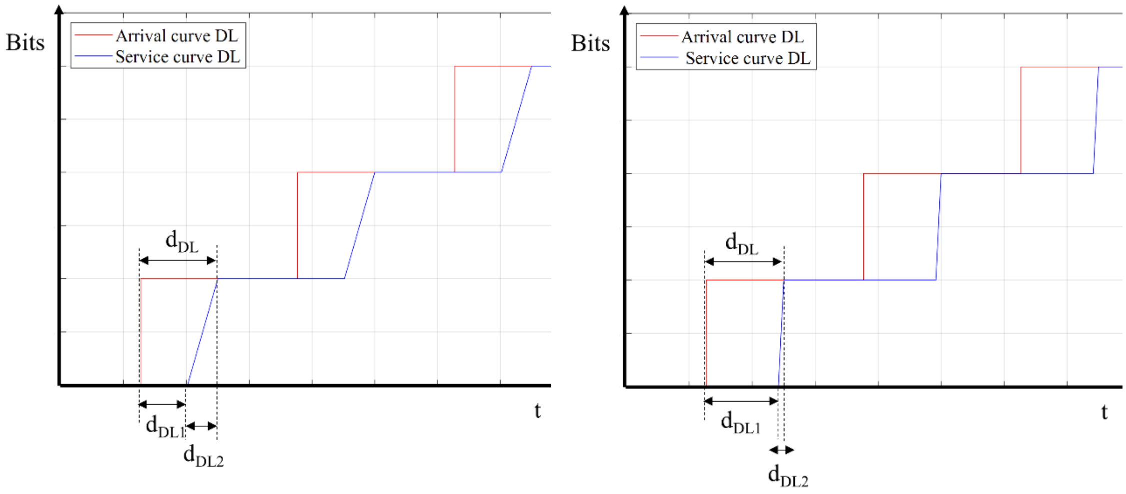
Case	Equations
1, 3	$\beta_{UL}(t) = B \cdot max(\left\lfloor \frac{t + Offset_{UL}}{c} \right\rfloor \cdot (tslot_{UL} + t_{ULRetr}), (t + Offset_{UL}) - \left\lceil \frac{t + Offset_{UL}}{c} \right\rceil \cdot (c - tslot_{UL} - t_{ULRetr}))$
1, 2	$\beta_{DL}(t) = B \cdot max\ (\left\lfloor \frac{t}{c} \right\rfloor \cdot (tslot_{DL} + t_{DLRetr}), t - \left\lceil \frac{t}{c} \right\rceil \cdot (c - tslot_{DL} - t_{DLRetr}))$
2, 4	$\beta_{UL}(t) = B \cdot max(\left\lfloor \frac{t + Offset_{UL}}{c} \right\rfloor \cdot tslot_{UL}, (t + Offset_{UL}) - \left\lceil \frac{t + Offset_{UL}}{c} \right\rceil \cdot (c - tslot_{UL}))$
3, 4	$\beta_{DL}(t) = B \cdot max(\left\lfloor \frac{t}{c} \right\rfloor \cdot tslot_{DL},\ t - \left\lceil \frac{t}{c} \right\rceil \cdot (c - tslot_{DL}))$
1, 3	$d_{UL1} = Offset_{DL} - tslot_{UL} - t_{ULRetr}$ $d_{UL2} = tslot_{UL} + t_{ULRetr}$
1, 2	$d_{DL1} = Offset_{UL} - tslot_{DL} - t_{DLRetr}$ $d_{DL2} = tslot_{DL} + t_{DLRetr}$
2, 4	$d_{UL1} = Offset_{DL} - tslot_{UL}$ $d_{UL2} = tslot_{UL}$
3, 4	$d_{DL1} = Offset_{UL} - tslot_{DL}$ $d_{DL2} = tslot_{DL}$

The obtained arrival and service curves (both DL and UL) along with the delays are represented in Figure 3.6 and Figure 3.7. Although the service curves analysed in the four cases are different, the calculated maximum total delay is the same. The maximum total delay corresponds to the length of the proposed superframe (c). This delay is graphically shown in Figure 3.8, taking into account the case 1 arrival and service curves.



(a) (b)

Figure 3.6: Obtained α_{UL} and β_{UL} in: (a) case 1 and 3 and (b) case 2 and 4.



(a) (b)

Figure 3.7: Obtained α_{DL} and β_{DL} in: (a) case 1 and 2 and (b) case 3 and 4.

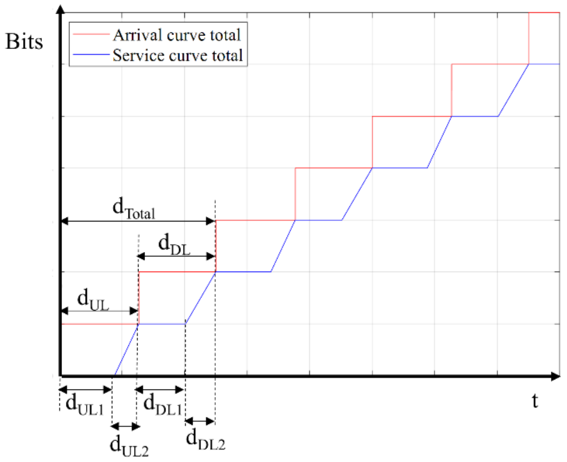


Figure 3.8: Obtained maximum total delay.

3.2.2 Evaluation

3.2.2.1 Simulation setup

To evaluate the performance of the proposed hybrid MAC scheme, a model in OMNeT++ simulator has been implemented. The simulated network architecture follows the architecture described in Section 3.1, where the hybrid network is formed by a PLC, an AP and several devices along the hybrid network. In this network, all the nodes exchange RT traffic with the PLC (simulating the sensor reading), and the PLC with all nodes (simulating the calculated values for the actuators). The traffic generation will be carried out periodically taking into account the control cycle of the system. The parameters of the simulated system are shown in Table 3.3 The IEEE 802.11g physical layer has been used because when no MIMO (Multiple-Input Multiple-Output) approach is used due to the introduced overhead, there are no significant advantages between using the physical layer of IEEE 802.11g or the physical layers of the most recent amendments of the IEEE 802.11 family[102], [103].

Table 3.3: Simulation parameters.

Simulation parameters	**Wired segment**	**Wireless segment**
Physical layer	IEEE 802.3	IEEE 802.11g ERP-OFDM
Data rate	100 Mbps	54 Mbps
Noise threshold	-	-90 dBm
Data payload	50 bytes	
Control cycle	1.212 ms (1 superframe)	
Number of devices	4 in each segment	
Number of APs	1 (channel 1)	
Number of PLCs	1	-
Number of Retr slots	-	4 for DL and 4 for UL
DL/DLRetr slot duration	70.4 µs (only DL)	65.75 µs
UL/ULRetr slot duration	70.4 µs (only UL)	35.75 µs (except the last UL) 65.75 µs (the last UL and ULRetr)
BE slot duration	52.8 µs (1st) 32.8 µs (2nd)	80 µs
SIFS duration	-	10 us

To simulate a realistic industrial environment for the wireless segment, small-scale fading channels have been taken into account, i.e., variations occur rapidly over a small distance. To this end, a channel that follows a Rayleigh distribution has been used to describe the worst possible scenario and a channel that follows a Rice Kr = 5 has been defined to describe an industrial channel with a smaller number of fades. In both cases, flat fading channels are considered. The simulations have been conducted by setting different values of Signal-to-Noise Ratio (SNR) over which PER have been measured. These values have been compared with the theoretical PER curves of each channel obtained through Monte Carlo simulations using the WLAN System Toolbox^{TM} provided by MATLAB. The obtained PER curves are loaded into OMNeT++. Then in OMNeT++, every time a device receives a packet evaluates if its reception is correct or no. For that, a device will consider a successful packet reception if the PER of the received packet is lower than a uniformly distributed random value in the range [0, 1]. This random value will change every time a packet is received.

These simulations have been performed at signal level considering: a preamble composed of 12 special symbols, a header composed of 1 OFDM symbol using BPSK (at 6 Mbps) and the rest of the packet composed of 2 OFDM symbols using 64-QAM.

The performance of the proposed scheme has been compared with the IsoMAC [54] proposal in terms of PER for the DL traffic because both propose a TDMA-based superframe structure with slots assigned to uplink and downlink traffic. Our proposal goes even further proposing a MAC scheme to control the wired segment that is synchronized with the proposed wireless MAC scheme making up a hybrid system. On the other hand, the percentage of DL retransmission and UL retransmissions slots unused has been calculated along with the MAC to MAC delays of the DL traffic, UL traffic and the whole cycle.

3.2.2.2 Simulation results

The performance of the proposed hybrid scheme has been compared with IsoMAC [54] in terms of PER of DL traffic. The results obtained are shown in Figure 3.9. In both cases, the results have been obtained with a confidence interval of 95%.

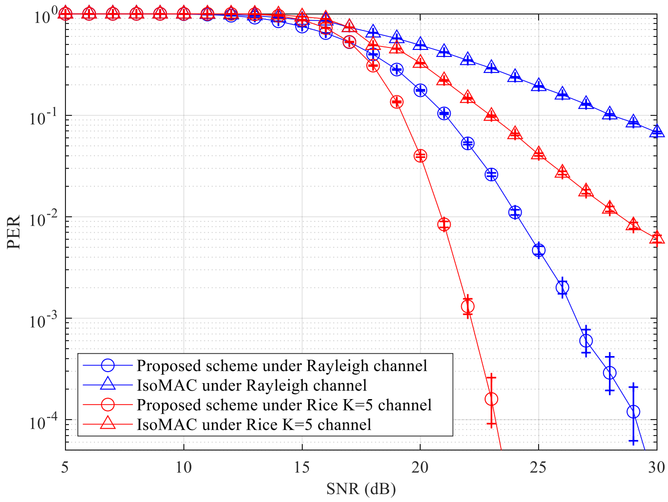


Figure 3.9: PER of the DL traffic under fading channels.

Must be taken into account, that with IsoMAC [54] DL traffic cannot be retransmitted until the UL slots are completed. This may compromise the state of the process by performing new sensor readings without having correctly received the outputs for the actuators. For the proposed hybrid application, the retransmission of that traffic after a new sensor reading has no sense. So, for an application like this, the recovery phase proposed in [54] would be relegated to the retransmission of UL traffic only.

Therefore, comparing the performance of our hybrid proposal with the scheme proposed in [54], a lower PER has been achieved. Given the limitation of the recovery phase proposed in [54] for the proposed application, DL traffic will only have one transmission and zero retransmission attempts. In contrast, with the proposed scheme, the DL traffic could retransmit in a control cycle once in the worst case, and in the best case, as many times as retransmission slots correspond to DL exist in the superframe.

On the other hand, the total PER of both DL and UL traffic for the proposed hybrid scheme is obtained and compared with the theoretical PER curves. These results, which are shown in Figure 3.10 and Figure 3.11, have been achieved under fading channel with a confidence interval of 95%.

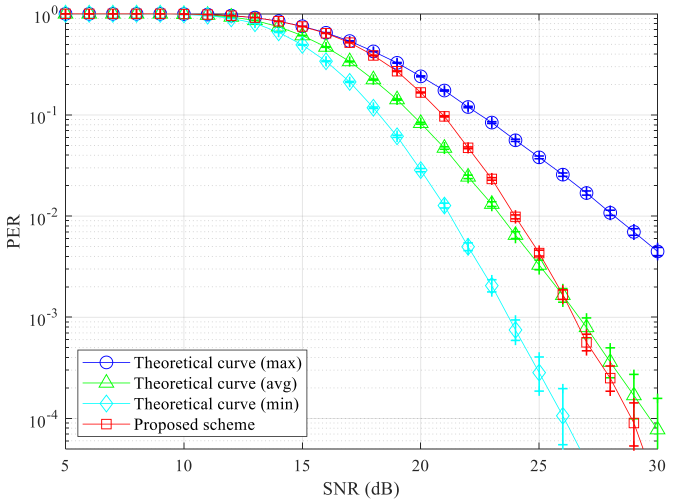


Figure 3.10: Total PER under Rayleigh channel.

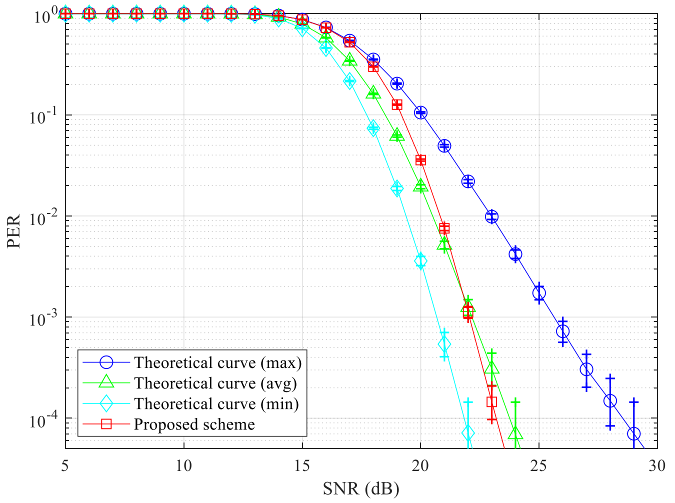


Figure 3.11: Total PER under Rice K=5 channel.

The figures show the minimum, average and maximum of the theoretical PER curves. The maximum theoretical PER curve refers to the worst case, i.e., each wireless device could retransmit once in a control cycle. In contrast, the minimum theoretical PER curve refers to the best case, i.e., the wireless device could retransmit as many times as retransmission slots correspond to DL exist in the superframe. The average curve, therefore, refers to the mean between these two curves. In the proposed scheme, when the SNR value is small, the resulted PER curve is similar to the maximum theoretical curve. As the SNR increases, the PER curve obtained for the proposed scheme starts to look like the average theoretical curve because the traffic requires fewer retries to be received correctly.

On the other hand, the percentage of DL retransmission slots unused and UL retransmissions slots unused has been calculated. In this way, it is possible to know how much free time slots would be on average for the transmission of either RT aperiodic traffic or BE in these slots. The results are shown in Table 3.4 and Table 3.5.

Table 3.4: Percentage of the unused retransmission slots under Rayleigh channel.

SNR (dB)	Unused DL Retr slots	Unused UL Retr slots
17	0.17 %	2.03 %
18	0.94 %	5.73 %
19	3.46 %	12.42 %
20	9.73 %	21.92 %
21	19.25 %	33.11 %
22	32.41 %	45.76 %
23	44.54 %	56.11 %
24	57.03 %	65.31 %
25	66.31 %	72.89 %
26	73.56 %	78.76 %
27	79.79 %	83.39 %
28	84.62 %	87.13 %

Table 3.5: Percentage of the unused retransmission slots under rice K=5 channel.

SNR (dB)	Unused DL Retr slots	Unused UL Retr slots
17	0.17 %	2.02 %
18	2.71 %	9.97 %
19	14.18 %	28.04 %
20	36.77 %	50.17 %
21	60.36 %	68.16 %
22	76.05 %	80.71 %
23	85.38 %	87.86 %

These results show that the higher the SNR, the bigger the percentage of the unused retransmission slots becomes. The reason is that as the SNR increases, the traffic requires fewer retries to be received correctly leaving unused retransmissions slots. Moreover, the difference between the obtained percentage of the unused slots for UL and DL retransmission is due to the acknowledgment mechanism used in each case.

Finally, the MAC to MAC delays of the DL traffic, UL traffic and the whole cycle have been calculated. The time taken from the packet arrival from the source's MAC layer to its successful reception in the destination's MAC layer is considered as MAC to MAC delay. For that, the Cumulative Distribution Functions (CDF) of the delays (only for under Rayleigh fading) have been evaluated. The results are obtained for a mean SNR of 24 dB, where the PER is about 10^{-2}, and for a mean SNR of 28 dB, where the PER is about 10^{-4}. The results of the minimum, maximum and average MAC to MAC delay are shown in Figure 3.12 and Figure 3.13.

The 100% of packets arrive at the receiver after waiting to access the medium a maximum of 39.2% of the duration of one control cycle for UL traffic, 46.6% of the duration of one control cycle for DL traffic and 96.6% of the duration of one control cycle for complete cycle considering the UL and DL traffic exchange for an SNR of 24 dB. For an SNR of 28 dB, the 100% of packets arrive at the receiver after waiting to access the medium a maximum of a maximum of 32.9% of the duration of one control cycle for UL traffic, 34.1% of the duration of one control cycle for DL traffic and 84.1% of the duration of one control cycle for complete cycle considering the UL and DL traffic exchange. The differences between the results obtained for UL and DL traffic are due to the length of the slots, being longer the slots used to transmit DL traffic, so the MAC to MAC delay is longer in this case.

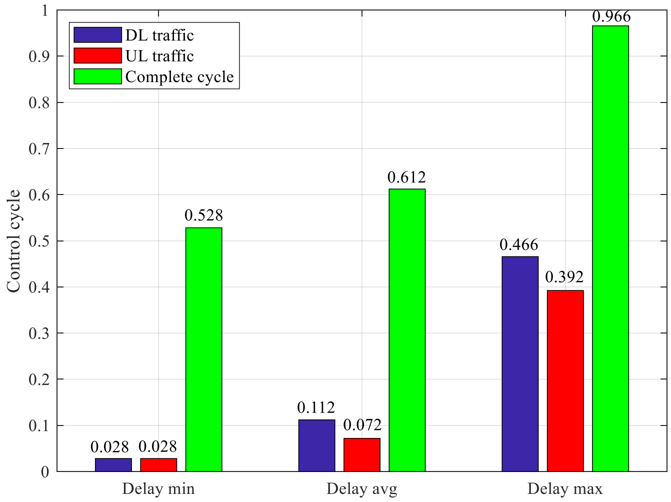


Figure 3.12: MAC to MAC delay under Rayleigh channel and an SNR of 24 dB.

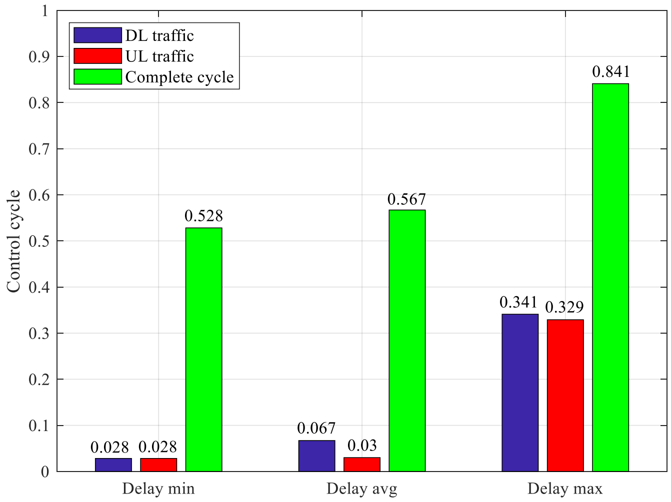


Figure 3.13: MAC to MAC delay under Rayleigh channel and an SNR of 28 dB.

According to the results, for every setup, the calculated theoretical bounds in Section 3.2.1.2 match with the obtained MAC to MAC simulations. The maximum MAC to MAC delay of the whole cycle is never greater than the theoretical bound, which corresponds to the length of the proposed superframe as stated in Section 3.2.1.2, i.e. the duration of the control cycle.

It is noteworthy that when evaluating the whole control cycle MAC to MAC delay, it is not relevant when the UL packet is received within the phase dedicated to transmitting the UL packets. Regardless of whether the UL packet is received in the first slot (dedicated to transmitting it) or in the last ULRetr slot, for the calculation of the MAC to MAC delay of the whole cycle, the full UL phase must be taken into account. In the same way, the BE interval must be taken also into account when evaluating the whole control cycle MAC to MAC delay.

3.3 Chapter summary

In this chapter a hybrid RT MAC scheme is proposed with the aim to expand the wired network used in industrial control applications to a wireless domain. The proposed MAC scheme is the main contribution of this chapter.

The proposed scheme, which is based on a deterministic TDMA superframe, supports periodic RT traffic, aperiodic RT traffic and BE traffic. The design of this MAC scheme is focused on guaranteeing the robustness and determinism required by control applications while ensuring that there is a seamless coexistence between both media. For this purpose, to control the wireless segment, a MAC scheme based on the IEEE 802.11 physical layer is proposed. In order to improve the reliability, retransmission mechanisms are added to the proposed wireless scheme.

In contrast, to control the wired segment, a proprietary RTE and TSN based MAC scheme is proposed. To interconnection of both networks, is made through an AP that will act as a bridge between both media—routing the packets from the wired network to the wireless network and vice versa.

Finally, a theoretical analysis has been carried out to study the validity of the proposed wireless MAC scheme and the performance of the proposed hybrid MAC scheme has been evaluated over small-scale fading channels through OMNeT++ simulations. Provided results show that the transmission of periodic RT traffic is not affected by the transmission of aperiodic or BE traffic. Moreover, results show that the transmissions and retransmissions are adapted to tight control cycles.

Chapter 4

Soft-handover algorithm for hybrid Distributed Control Systems

One of the main objectives of this thesis is to propose a mechanism to incorporate mobile devices to the hybrid MAC scheme proposed in Chapter 3. This mechanism allows to expand the application area and obtain even more benefits from using wireless solutions. So, in this chapter, a novel soft-handover algorithm is proposed that focuses on guaranteeing an uninterrupted communication during the handover process without the need for a second radio interface like the proposals of the literature and with a reduced growth in network overhead. The first section of this chapter describes the proposed soft-handover algorithm as well as its restrictions. In Section 4.2 the simulation setup and the results obtained through OMNeT++ simulations are presented.

4.1 Proposed soft-handover algorithm

As stated in Chapter 2, the most critical industrial applications with mobility requirements require soft-handover algorithms in which the interruption of the communication is avoided, maintaining the connection between both APs during the execution of the handover. Nevertheless, the handover algorithms proposed in the literature are not designed to be used in critical industrial applications, so when a handover is performed, the communication between the associated AP and the node is interrupted causing packet losses. In order to solve this issue, an improved soft-handover algorithm is proposed that focuses on guaranteeing an uninterrupted communication during the handover process without the need for a second radio interface like the proposals of the literature and with a reduced growth in network overhead.

Moreover, to avoid the interruption of the communication, the device that initiated the handover process (STA_H) will momentarily have slots assigned in both the current (AP_C) and target (AP_T) APs. Every notification between APs will be carried out through communications during the non-scheduled time windows of TSN scheduler. To reduce the time needed to execute the handover process, and in addition to increasing the reliability of the process, the state of the handover will be included in the MAC-level headers of the RT frames transmitted by the wireless devices. For that, the IEEE 802.11 MAC headers must be modified slightly.

Finally, the considered algorithm does not require neither a discovery phase nor an authentication phase. This is because in critical industrial applications, the nodes that form the hybrid network are preconfigured in advance, i.e. no external wireless nodes can be connected at the runtime. Hence, the number of APs and the basic information (the control cycle duration, the used radio channel, the authentication information etc.) are known beforehand.

4.1.1 MAC headers of the IEEE 802.11 RT data frames

Along with the proposed wireless MAC layer in Chapter 3 in order to exchange RT data frames deterministically, it is also necessary to customize the MAC headers of the RT data frames in order to obtain a reduced control cycles. The MAC header of the IEEE 802.11 standard is too large for the considered application. The minimum IEEE 802.11 data frame MAC header is 24 bytes as shown in Figure 4.1 [46].

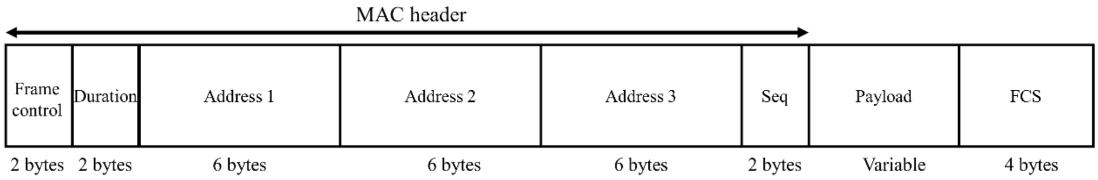


Figure 4.1: Minimum IEEE 802.11 data frame MAC header

So, a new compressed MAC header is proposed to use in RT data frames. The proposed MAC format is shown in Figure 4.2. The IEEE 802.11 MAC headers of the RT frames have been modified and shortened with two objectives: Firstly, to reduce the inefficiencies related to the packet overhead—considering the reduced amount of information that is sent in the industrial communications [7]—, and secondly, to include the request and resolution signals of the handover.

The first three fields (frame control, duration and address 1) and the last field, Frame Check Sequence (FCS), of the standard IEEE 802.11 data frame MAC header shown in Figure 4.1, constitute the minimal frame format of the IEEE 802.11 standard. So, they have been kept in our proposal as shown in Figure 4.2. In addition, the sequence field, which is part of the standard data packet header and is formed by 16 bits, has been included as well. In the standard IEEE 802.11 , out of the 16 available bits of the sequence field, 12 identify the frame and the remainder 4 identify the fragment. In the proposed reduced MAC header, these last 4 bits have been redefined as Handover (HO) and will be used to indicate the state of the handover process.

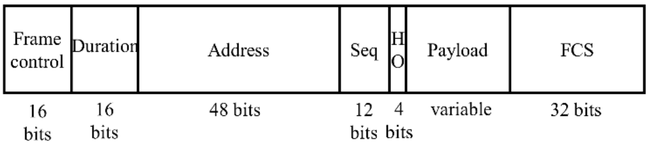


Figure 4.2: Proposed MAC header of the RT data packets.

The HO field is used to make all notifications of the handover process, so it is not necessary to send additional frames. This in addition to be predictable allows not to increase the wireless traffic during a handover. Thus, each time a node wants to start with the handover process it will only have to indicate it in the HO field of the MAC header of the periodic RT data packet exchanged with the AP (which it will then send to the PLC). In this way, the time required to execute the handover process is reduced as well as the network overhead due to a handover is not increased.

4.1.2 *Phases of the proposed handover*

The preparation and execution of the proposed soft-handover algorithm consists of five phases: communication before the handover, pre-handover measurements, handover decision, preparation of the handover process and handover execution. To help to understand the description of each of the phases, a simplified diagram of the proposed handover algorithm is shown in Figure 4.3.

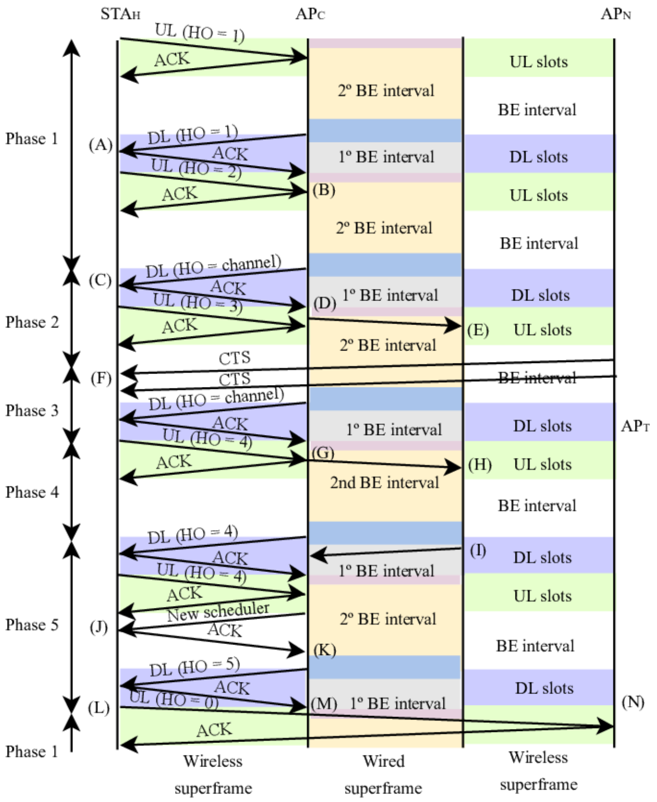


Figure 4.3: Proposed soft-handover algorithm.

4.1.2.1 Communication before the handover (Phase 1)

At runtime, the communication between the node and the AP_C will be made according to the proposed wireless MAC scheme in Chapter 3. The nodes will exchange RT data packets periodically with the AP_C and vice versa. When a wireless node receives RT data packets send by the AP_C, it should assess the quality of the link with the AP_C. In case the quality of the link falls below a threshold for a predetermined time (T1), the STA_H should look for a candidate AP (AP_N) (Point A in Figure 4.3). This event will be used as a warning to a possible handover and will initiate the second phase of the proposed handover process (Figure 4.4). The intention of the STA_H to find an AP_N will be notified to its AP_C through the HO field (HO = 2) of the header of its next periodic RT data packet sent during its UL slot.

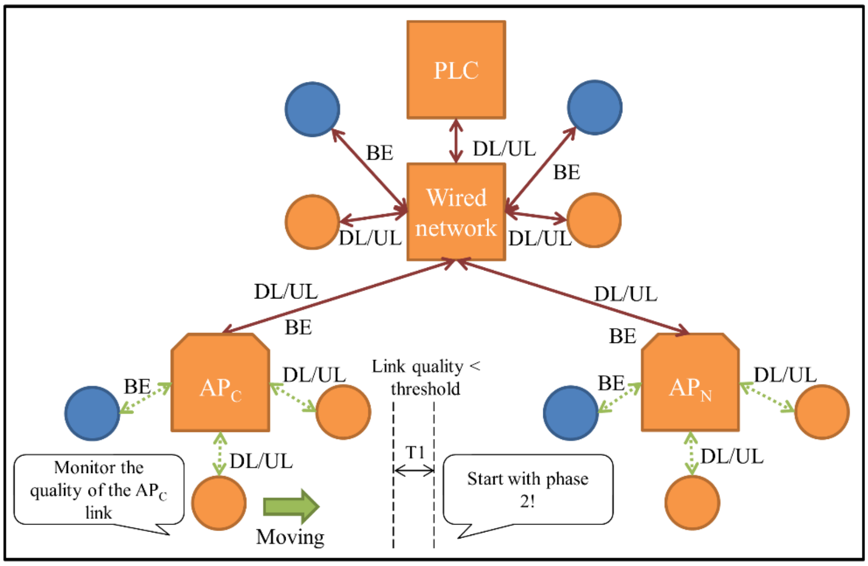


Figure 4.4: Communications before handover (Phase 1).

4.1.2.2 Pre-handover measurements (Phase 2)

When the AP_C receives the intention of the STA_H to find a new AP (Point B in Figure 4.3), it will send, through the HO field of the header of its next DL RT data packet, several parameters related to one AP_N of the STA_H (Point C in Figure 4.3). The shared information included among others, the used radio channel. Given that the DL packets are acknowledged, the AP_C will know if the STA_H has received the channel to sense (Point D in Figure 4.3).

In the affirmative case, the AP_C will notify the AP_N, through communications during non-scheduled time windows of TSN scheduler (Point E in Figure 4.3), that it must occupy the following BE intervals of the proposed wireless MAC scheme sending Clear-To-Send (CTS) packets. In this way, the STA_H can evaluate the quality of the AP_N link by listening the CTS packets sent by the AP_N in its corresponding radio channel. Given the possibility of fading due to the variation in the channel paths, several intervals of BE periods may be necessary to estimate the quality of the link.

Note that it may be the case that the AP_C assigns to the STA_H an AP_N to sense that is not within the range of the STA_H. To solve this problem, first, each AP_C and the devices associated with it must communicate on a different radio channel than the AP_C's AP_Ns. Second, the APs will be placed in such a way that an AP only has neighbouring APs in non-overlapping channels, i.e. the spectral overlap does not affect the performance of networks which use them. The proposed AP distribution is shown in Figure 4.5. In the case of IEEE 802.11g standard, the non-overlapping channels are 1, 6 and 11 . Third, a simple algorithm is proposed so that an STA_H can sense the link of an AP_N within its range. This algorithm allows a STA_H that does not receive any CTS frame during the BE interval because it is out of the range of the assigned AP_N to notify it to the AP_C. This notification will be carried out through the HO field of the MAC header of the next periodic RT data frame sent during the assigned UL slot. When the AP_C receives this information, it will send to the STA_H the channel of its other AP_N. In this way, we make sure that regardless of where the STA_H is located, it will find an AP_N to sense.

The information related to the handover process exchanged during this handover phase has been represented through Algorithm 4.1. Note that in the case of wireless segment, the information related to the handover is exchanged through the HO field of the RT data packets sent during the RT period of the proposed wireless MAC.

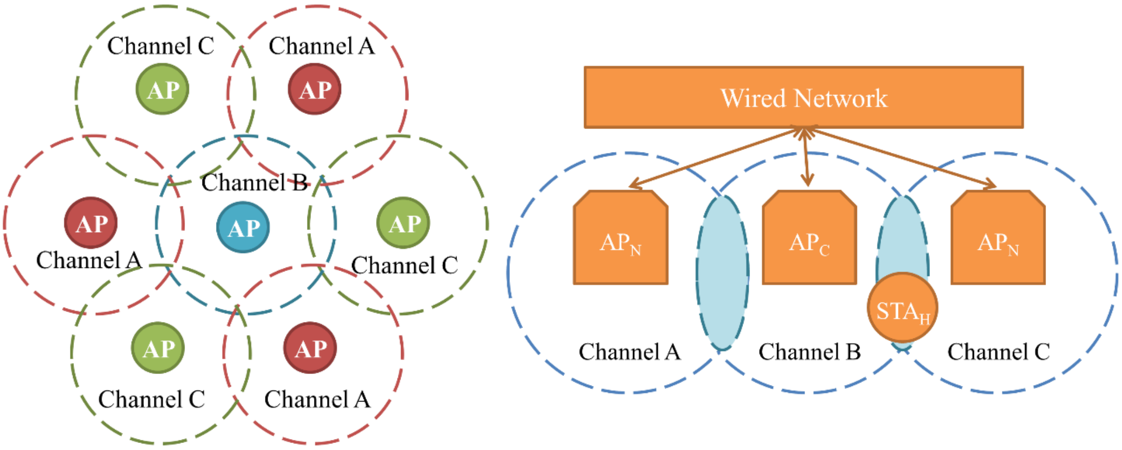


Figure 4.5: Proposed AP distribution.

Algorithm 4.1: Pre-handover measurements.

```
1) The AP$_C$ receives the intention of the STA$_H$ to find an AP$_N$:
    Wait until DL phase of the wireless superframe.
    a) If it is the second time in the step 1) during the same handover process.
        Notify the previous selected AP$_N$ to stop sending CTS during the BE phase of the
        wireless frame.
2) If DL slot assigned to STA$_H$:
    Send information to STA$_H$ from one of its neighbour AP$_N$.
    Wait until ACK frame.
3) If
    a) an ACK is received:
        Wait until 2º BE interval of the wired superframe.
    b) a NACK or no response is received:
        Go to step 2).
4) If 2º BE interval of the wired superframe:
    AP$_C$ notifies AP$_N$ to occupy sending CTS frames the following BE intervals of the
    wireless superframe.
    Wait until the BE interval of the wireless superframe.
5) If BE interval of the wireless superframe:
    AP$_N$: send CTSs.
    STA$_H$: listen to the wireless medium.
    a) If STA$_H$ receives CTSs:
        Repeat step 5) several times in order to estimate the quality of the channel → Then
        go to the phase 3 of the handover process.
    b) If STA$_H$ does not receive CTSs:
        Notify the AP$_C$ during the transmission made during the next UL slot assigned to
        the STA$_H$.
        Go to step 1) → the AP$_C$ will send information to STA$_H$ from its other neighbour
        AP$_N$.
```

4.1.2.3 Handover decision (Phase 3)

For the decision of whether the execution of the handover process is necessary or not, the instant in which the quality of the AP$_N$ link exceeds that of the AP$_C$ link (plus a hysteresis) will be taken as a trigger as defined in (4.1). It is worth mentioning that with this trigger, conditions based on both the AP$_N$ and the AP$_C$ are evaluated. The Received Signal Strength Indicator (RSSI) is the metric taken into account to measure the quality of the link.

As shown in Figure 4.6, the handover process will be executed as long as the condition defined in (4.1) is met during a time interval (T2) used to avoid a ping-pong effect. At this point, the AP$_N$ becomes the target AP (AP$_T$) with which the STA$_H$ wants to associate (Point F in Figure 4.3).

$$Link_N - Hys > Link_C + Off. \tag{4.1}$$

However, if during the defined T2 time interval, the condition defined in (4.2) is met, it will be considered that it is not necessary to execute the handover process with the AP$_N$.

$$Link_N + Hys < Link_C + Off. \tag{4.2}$$

$Link_N$ and $Link_C$ correspond to the measures of the quality of the AP$_N$ and AP$_C$ links, respectively. A hysteresis (*Hys*) and an offset (*Off*) values are considered to ensure that the handover will improve the link quality and avoid a passive ping-pong effect.

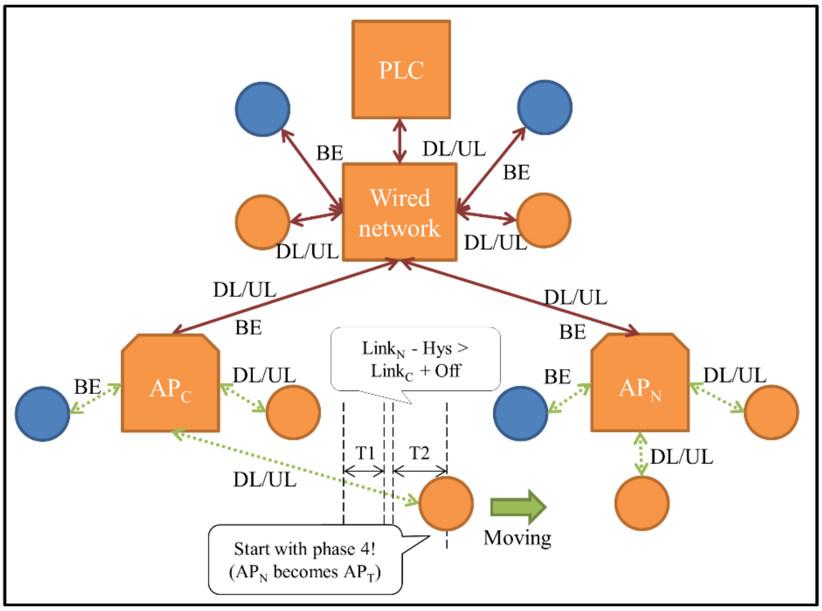


Figure 4.6: Communications during handover decision (Phase 3).

4.1.2.4 Preparation of the handover process (Phase 4)

At this moment the STA$_H$ must notify the decision to make a handover to the AP$_C$ setting the state of the handover process in the HO field (HO = 4) of the next UL RT data packet.

When the AP$_C$ receives this information (Point G in Figure 4.3), it will notify the AP$_T$ that there is a STA$_H$ that wishes to associate with it (Point H in Figure 4.3). This notification is made during non-scheduled time windows of TSN scheduler.

Note that in order to not compromise the operation of the system, the network must be dimensioned so that an AP can host all the nodes that form the wireless network. Although, this entails an over sizing of the wireless superframe, it also guarantees that an AP is able to manage all wireless nodes given an overload situation. That is why an AP$_T$ will never reject a handover request.

On the other hand, to maintain the backward compatibility with the interface between IEEE 802.11 and higher software layers, once the AP$_T$ realizes that there is a STA$_H$ that wants to associate with it, the AP_T must send itself an association request primitive as if it had been sent by the STA_H. Thereby, the STA_H will be associated with the AP_T but it will not be able to communicate with it yet. Moreover, the AP_T should recalculate the scheduler to be able to assign slots to the STA_H and inform the other STAs associated accordingly. Before starting to use the new scheduler, the AP_T must be sure that all devices previously associated with it are aware of the new scheduler. Otherwise, the operation of the system could be compromised. As stated in Chapter 3, the transmission of the changes in the scheduler by an AP will be made during the BE period of the proposed wireless superframe and the transmission is immediate without waiting for a contention.

Once all the nodes associated with the AP_T are aware of the change in the scheduler, the STA_H will still be associated with the AP_C; but it will have all the information of the AP_T and will be waiting to receive its new scheduler to finish with the association process. Finally, the AP_T will send a last packet to the AP_C, through the non-scheduled time windows of the TSN scheduler, indicating the scheduler that the STA_H must follow when the execution of the handover finishes (Point I in Figure 4.3).

4.1.2.5 Handover execution (Phase 5)

At this point, the AP_T must send the scheduler to the STA_H during the BE phase of the wireless MAC scheme. When the STA_H receives this new scheduler (Point J in Figure 4.3), it will momentarily have one DL and one UL slot slots assigned in the superframe of both AP_C and AP_T. In this way, it is guaranteed that there will be no interruption in the communication during the execution of the handover. Despite having slots assigned in both frames, the STA_H will only transmit in one of them. This depends on whether the STA_H has received the scheduler sent by the AP_T through the AP_C or not. To prevent unnecessary retransmissions, if the STA_H has not correctly received the AP_T's scheduler, the latter will not ask to retransmit a packet if the STA_H has communicated correctly with the AP_C and vice versa. That is, if STA_H has not notice that it has time slots assigned in the AP_T scheduler, the AP_T will not ask it to retransmit a packet if the STA_H has communicated correctly with the AP_C. In these cases, the AP_C will inform about the successful reception of the STA_H's packet to the AP_T through the non-scheduled time windows of the TSN scheduler. Similarly, if STA_H is communicating correctly with the AP_T, the AP_T will inform about the successful reception to the AP_C through the non-scheduled time windows of the TSN scheduler.

Finally, when the STA_H receives the AP_T's scheduler, it must send an ACK to their AP_C confirming the reception of the new scheduler (Point K in Figure 4.3). This confirmation will be again carried out during the period dedicated to the transmission of the BE traffic of the proposed wireless MAC scheme. Both the STA_H and the AP_C will not disassociate even though the latter receives the confirmation and will continue using the AP_C scheduler until the end of the DL slots of the next frame (field HO = 5). This is necessary because the scheduler that follows the wired nodes remains unchanged, and the packets sent by the STA_H to the PLC and vice versa are still transmitted through the AP_C. As soon as the DL interval ends, the STA_H will no longer be associated with the AP_C. The AP with which the STA_H will be associated from now on is the AP_T. Moreover, the STA_H will no longer have assigned time slots in the AP_C's superframe and will only communicate with the AP_T (Point L in Figure 4.3).

Again, to maintain the backward compatibility with IEEE 802.11 standard, the AP_C must send itself a disassociation request primitive as if it had been sent by the STA_H. From this point and onwards, the AP_T will become the AP_C of the STA_H and the one that was the AP_C will become an AP_N (Point M and N in Figure 4.3).

Finally, once again, it will be necessary to perform a reschedule on the AP that was the AP_C and this one must notify the wired network about the new change in the schedulers of the superframes. At this point, STA_H will communicate based on the proposed wireless MAC scheme previously described in Phase 1 (Figure 4.7).

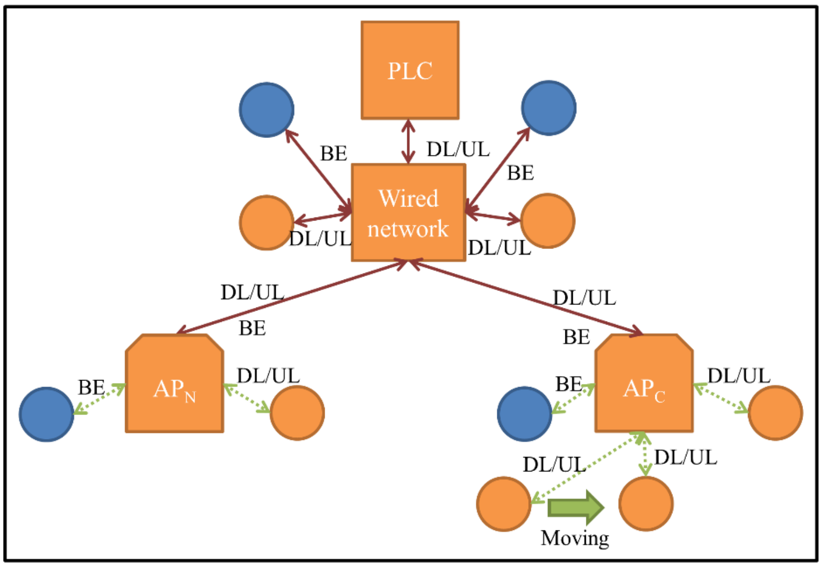


Figure 4.7: Communications after a handover.

4.1.3 *Restrictions of the proposed soft-handover algorithm*

There are some restrictions regarding the proposed soft-handover algorithm:

1) Each AP_C, the devices associated with it and the AP_C's AP_Ns must communicate on a different radio channel.
2) Each APs in the network must be placed in such a way that an AP only has neighbours in the non-overlapping channels (there is no interference between the transmissions of the APs in the same channels).
3) The network must be dimensioned so that an AP can control the access to the wireless medium of a maximum number of devices at a given time, without compromising the operation of the system (a minimum number of slots for retransmissions and the shortest duration for the BE interval are defined).

4.2 Performance evaluation

4.2.1 *Simulation setup*

To evaluate the performance of the proposed soft-handover algorithm along with the proposed hybrid MAC scheme defined in Chapter 3, a model in OMNeT++ simulator has been implemented. The wireless MAC scheme and the proposed handover algorithm work on top of the IEEE 802.11g Orthogonal Frequency Division Multiplexing (OFDM) physical layer.

The simulated network architecture follows the architecture described in Chapter 3. Once again, since the critical industrial applications consist of about 20 devices [10], 20 devices are considered for the wired segment and other 20 devices for the wireless segment. Moreover, the wireless nodes will be mobile with a maximum speed of 30 km/h, i.e. the maximum speed used in most critical industrial applications [10]. In this network, all the nodes exchange RT traffic with the PLC (simulating the sensor reading), and the PLC with all nodes (simulating the calculated values for the actuators). The traffic generation will be carried out periodically taking into account the control cycle of the system. The parameters of the simulated system are shown in Table 4.1. To choose the channel switching time, the measurements done with the fast lock mode of the commercial AD9361 [104] radio frequency transceiver have been taken as a reference.

Table 4.1: Simulation parameters.

Simulation parameters	**Wired segment**	**Wireless Segment**
Physical layer	IEEE 802.3	IEEE 802.11g ERP
Data rate	100 Mbps	24 Mbps
Transmission frequency	-	2.412 GHz
Noise threshold	-	-90 dBm
Data payload	5 bytes	
Control cycle	3.481 ms (1 superframe)	
Channel switching	-	7.5 us
Number of devices	20	
Number of APs	3 (channels 1, 6 and 11)	
Number of PLCs	1	-
Number of Retr slots	-	At least 5 for DL and 5 for UL
Device speed	-	30 km/h
DL/DLRetr slot duration	8.64 µs (only DL)	69.75 µs
UL/ULRetr slot duration	8.64 µs (only UL)	35.75 µs (except the last UL) 69.75 µs (last UL and ULRetr)
SIFS duration	-	10 us
BE slot duration	510.49 µs (1st) 453.99 µs (2nd)	At least 139.5 µs At most 1 superframe

For assessing the performance of the proposed soft-handover algorithm, the average delay of the handover execution, the RT packet losses during the handover and the AP occupation have been evaluated. These analyses have been done taking into account several configuration setups, which involve the following parameters: a range of threshold values defined in phase 1 of the proposed handover algorithm (Table 4.2, leftward), a range of hysteresis (*Hyst*) and offset (*Off*) values defined in phase 3 of the proposed handover algorithm (Table 4.2, rightward). Different combinations of these three parameters have been considered in order to know which of them is the most influential.

Also, the analysis have been carried without taking into account nodes with BE traffic to transmit and taking into account 20 nodes trying to transmit BE traffic per control cycle. On the other hand, the obtained MAC to MAC delay has been evaluated for assessing the performance of the proposed hybrid MAC scheme along with the proposed soft-handover algorithm. These results will be compared with the theoretical bounds obtained in Section 3.2.1.2.

To obtain the results, the mobile devices have been placed randomly within a predefined area and the nodes will be able to move freely through it. The nodes will follow, a random movement pattern that is established in OMNeT++. Finally, to minimize any randomness in the results, each evaluation has been performed using several seeds.

Table 4.2: Simulated configurations (Regarding phase 1 threshold, *Hys* and *Off*).

Condition	**Threshold**	
	Rx power (dBm)	**PER**
I	Ch1: -75	10^{-1}
	Ch2: -73	
II	Ch1: -72	10^{-2}
	Ch2: -69	
III	Ch1: -69	10^{-3}
	Ch2: -66	
IV	Ch1: -66	10^{-4}
	Ch2: -62	

Setup	***Hyst* (dB)**	***Off* (dB)**
1	0	0
2		2
3		4
4	2	0
5		2
6		4
7	4	0
8		2
9		4

4.2.1.1 Simulated industrial channel models and channel attenuation vector

To simulate a realistic industrial environment, two industrial channel models have been taken into account (with Root Mean Square (RMS) delay spreads of 58 ns and 29 ns, respectively, [105], noted as Channel 1 (Ch1) and Channel 2 (Ch2)). In Table 4.3 the characteristics of the modelled channels are summarized. These channels have been modelled using the WLAN System Toolbox™ provided by MATLAB to obtain the PER as a function of the instantaneous reception power. The obtained curve has been loaded into OMNeT.

Table 4.3: Characteristics of the modelled channels.

Characteristics	**Channel**	
	1	**2**
Rms delay spread (ns)	58	29
Average gain of the paths (dB)	[-3 0 -15 -7 -10 -15]	[0 -10 -11 -22 -40 -40]
Delays of the paths (ns)	[0 50 100 150 200 250]	
Distribution	Rayleigh distribution with Non-Line-of-Sight (NLOS) conditions	

On the other hand, to model the small-scale fading of the channels (due to the variation in time of the impulse response of the channel), a vector with the variation in the channel attenuation has been generated in MATLAB and loaded into OMNeT. This vector includes a temporal variation that depends on the established maximum Doppler shift and transmission frequency.

The impact of the inclusion of these two effects (the fixed attenuation of the channel that depends mainly on the relative position between the elements that are communicating, and the temporal variation of the channel caused by the multipath), can be seen in Figure 4.8. The curves shown in Figure 4.8 has been obtained for a Doppler shift of 67.046 Hz (associated to a maximum speed of 30 km/h), the IEEE 802.11g physical layer, a data rate of 24 Mbps and 60-bytes packet length (includes all protocol overhead). It should be noted that Channel 1 is harder than Channel 2, despite the shorter delay spread. This is because the combination of Rayleigh fading on the shorter delay spread causes a higher deep-fading probability. That is why, for the same mean SNR, Channel 2 obtains a lower PER value.

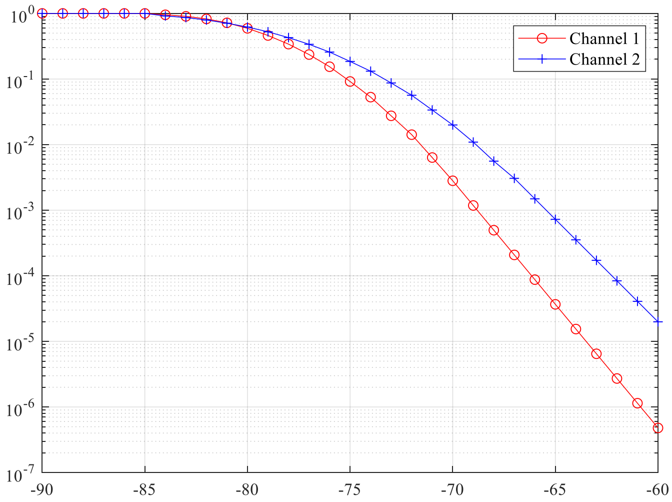


Figure 4.8: PER under the modelled industrial channels (Doppler shift of 67.046 Hz).

4.2.2 Simulation results

The performance of the proposed soft-handover algorithm has been compared to the Layer 2 IEEE 802.11 handover and with the proposed handover algorithms in the literature [65], [70] to confirm that it is an algorithm that ensures uninterrupted communication during the handover process. The comparison has been made in terms of average delay and packet losses during the handover execution. The algorithms in [65], [70] have been chosen because, although they do not completely avoid the interruption of the communication, they manage to optimize/eliminate the scanning phase, which is the most time-consuming phase of the entire handover process (≈ 90% of handover delay [64]). Moreover, the evaluated handover algorithms have been combined with the hybrid MAC scheme described in Chapter 3.

For the evaluation of the handover execution delay in the Layer 2 IEEE 802.11 handover and the solutions proposed in [65], [70], only association and rescheduling phases have been considered. The triggering phase can be omitted because the triggering time will not affect the total delay of the handover when the network configuration forces the station (setting a threshold) to change the AP before the condition of the channel deteriorates. The scanning can be omitted because the decision to carry out the handover has not yet been made. In [65], [70] algorithms, the criterion used to select the target AP is slightly modified with respect to the one defined in the proposed soft-handover algorithm. In this case, the offset value defined in (4.1) and (4.2) is not taken into account, as stated in [65], [70]. For the Layer 2 IEEE 802.11 handover the same criterion is used as in the proposed soft-handover algorithm and during the scanning phase, only the selected channels have been scanned. Moreover, as defined in the proposed soft-handover algorithm, the authentication done during the initialization phase of the network will be enough, since no external wireless device can be connected at runtime in industrial applications. So, no new node/candidate AP authentication is required during the handover execution. Finally, in [65], [70] the association phase is carried out as defined by the Layer 2 IEEE 802.11 handover.

On the other hand, for the evaluation of the proposed soft-handover delay, the first two phases of the algorithm have been omitted, because the decision to carry out the handover has not yet been made. It should be noted that the interruption of the communication is avoided with the proposed algorithm, because the mobile device will momentarily have slots in both the current and target APs, whereas the handover proposals of the studies under discussion [65], [70] and Layer 2 IEEE 802.11 handover will experience a communication interruption during association and rescheduling phases. In all the results below, the time needed to do the channel switching is included in the average delay results. Finally, in all the simulations, a fixed Doppler shift, associated with a maximum speed of 30 km/h, has been considered.

4.2.2.1 Average delay and packet losses during the handover

4.2.2.1.1 Proposed soft-handover algorithm

The measured average delays and packet losses during the execution of the proposed soft-handover algorithm, in combination with the MAC schemes defined in Chapter 3, are shown in Table 4.4 and Table 4.5. In Table 4.6, an overview of the results related to the average packet losses per handover can be seen.

First, unlike the algorithms defined in the two studies under discussion [65], [70] and in the Layer 2 IEEE 802.11 handover process, with the algorithm proposed in this chapter, the nodes trying to transmit the BE traffic during the BE period of the MAC scheme do not affect the handover execution at all. This is because the request and resolution of handover are included in the headers of the RT frames sent by the wireless devices during the RT interval of the MAC scheme. This way, additional packets related to the handover process are avoided (e.g. for the association) during the BE period as it is done in the proposals under discussion. With the proposed soft-handover algorithm, the only additional transmission made between the AP and the node during the BE period are related to rescheduling.

Table 4.4: Proposed soft-handover (under threshold conditions I and II).

Setup	**Average Packet Losses per Handover**				**Average Handover delay (normalized to the control cycle)**			
	Condition I		**Condition II**		**Condition I**		**Condition II**	
	Ch1	**Ch2**	**Ch1**	**Ch2**	**Ch1**	**Ch2**	**Ch1**	**Ch2**
1	1.133	1.003	0.0773	0.0794	6.82	5.84	4.79	4.81
2	0.919	0.796	0.0582	0.0598	5.76	4.74	3.77	3.78
3	0.749	0.584	0.0391	0.0404	4.72	3.76	2.76	2.77
4	1.157	0.987	0.0779	0.0807	6.79	5.82	4.81	4.82
5	0.938	0.784	0.0574	0.0595	5.73	4.72	3.71	3.73
6	0.726	0.573	0.0386	0.0407	4.7	3.78	2.77	2.79
7	1.165	0.998	0.0779	0.0804	6.78	5.8	4.79	4.81
8	0.931	0.772	0.0568	0.0603	5.72	4.71	3.71	3.73
9	0.717	0.564	0.0392	0.0399	4.71	3.77	2.78	2.81

Moreover, it is shown that the obtained average delay, and consequently the packet losses are very dependent on the selected hysteresis, offset and threshold values. On the one hand, the lower the threshold (Condition I), the higher the duration of the average delay is and the greater the number of packet losses is. This is because the link of the AP to which we are associated is sufficiently deteriorated to require more control cycles to execute the handover process. Also, in these cases, fewer handovers occur, given the deteriorated state of the link. It must be taken into account that, in this case, the higher the value of the hysteresis and the offset, the lower the average delay becomes, and less RT packets are lost. Given the temporal variation of the channel, a node can be considered an AP (as a candidate) incorrectly, or the decision to search for a candidate AP can be made, when the conditions of the current AP channel have deteriorated to the point of not being able to guarantee satisfactory communication. Both situations can arise by choosing incorrect offset and hysteresis values.

Table 4.5: Proposed soft-handover (under threshold condition III and IV).

Setup	**Average Packet Losses per Handover (x10^{-3})**				**Average Handover delay (normalized to the control cycle)**			
	Condition III		**Condition IV**		**Condition III**		**Condition IV**	
	Ch1	**Ch2**	**Ch1**	**Ch2**	**Ch1**	**Ch2**	**Ch1**	**Ch2**
1	5.72	5.87	0.34	0.42	3.75	3.77	2.79	2.81
2	3.83	4.07	0.32	0.39	2.75	2.76	2.74	2.75
3	3.7	3.88	0.31	0.37	2.76	2.76	2.74	2.75
4	5.71	5.88	0.35	0.42	3.73	3.75	2.8	2.82
5	3.9	4	0.32	0.4	2.73	2.74	2.72	2.73
6	3.62	3.75	0.31	0.37	2.75	2.76	2.75	2.75
7	5.86	5.85	0.34	0.42	3.75	3.76	2.78	2.8
8	3.93	4.02	0.36	0.41	2.74	2.75	2.72	2.72
9	3.66	3.78	0.29	0.38	2.74	2.74	2.75	2.75

Table 4.6: Proposed soft-handover: overview.

Setup	**Average Packet Losses per Handover (in %)**							
	Condition I		**Condition II**		**Condition III**		**Condition IV**	
	Ch1	Ch2	Ch1	Ch2	Ch1	Ch2	Ch1	Ch2
1	8.72	9.12	0.859	0.882	0.082	0.084	0.0067	0.0084
2	8.36	8.84	0.831	0.854	0.077	0.081	0.0064	0.0079
3	8.32	8.34	0.782	0.807	0.074	0.078	0.0062	0.0074
4	8.9	8.97	0.866	0.897	0.082	0.084	0.0069	0.0084
5	8.52	8.71	0.82	0.85	0.078	0.08	0.0064	0.008
6	8.07	8.18	0.772	0.814	0.072	0.075	0.0062	0.0074
7	8.96	9.07	0.865	0.893	0.084	0.084	0.0068	0.0084
8	8.46	8.58	0.811	0.862	0.079	0.080	0.0071	0.0089
9	7.97	8.05	0.784	0.799	0.073	0.076	0.0058	0.0076

It must be taken into account that the threshold is the most critical parameter. For example, if the results obtained in Condition II, III and IV of Setup 9 are considered, the measured average delay is similar in all cases but the same cannot be said about the packet losses per handover. While in the worst case (Condition II) 0.784 % and 0.799 % of the RT packets are lost on average in Ch1 and Ch2 respectively, in the best case (Condition IV), 0.0058 % and 0.0076 % of the RT packets are lost on average in Ch1 and Ch2 respectively. This is two orders lower. In contrast, for the same threshold value, only significant differences in the delay are shown. For example, if the results obtained in Setup 1 and 9 of Condition I are considered, the average delay is about 35% lower in the case of Setup 9 than in the case of Setup1, but the average RT packet losses is about 10 % lower in the case of Setup 9 than in the case of Setup 1. Therefore, it can be concluded that the delay obtained is not entirely proportional to the number of packet losses.

Finally, note that the packet losses shown in Table 4.4, Table 4.5. and Table 4.6 are not related to the interruption of the communication during the handover. The losses are due to the wireless channel itself.

4.2.2.1.2 Comparison

The performance of the proposed soft-handover algorithm has been compared with the proposed handover algorithm in [65], [70] and with the Layer 2 IEEE 802.11 handover mechanism in terms of average delay and packet losses during the handover execution. The obtained results are shown in Table 4.7 and Table 4.8. The results are shown only for a threshold of -66 dBm because the results obtained with [65], [70] and Layer 2 IEEE 802.11 handover mechanism are similar at higher threshold values, and at lower threshold (< -66 dBm), the delay and the packet losses increase due to the deterioration of the link.

Table 4.7: Average handover delay (threshold = -66 dBm, Off = 0 dB).

Hyst (dB)	**Nº BE nodes**	**Average Handover delay (normalized to the control cycle)**							
		Ch1				**Ch2**			
		[65]	[70]	**Layer 2 IEEE 802.11**	**Our proposal**	[65]	[70]	**Layer 2 IEEE 802.11**	**Our proposal**
0	0	9.58	7.96	9.87	3.77	10.76	8.56	10.91	2.79
	20	13.97	11.98	14.97		15.01	12.53	16.01	
2	0	8.94	7.46	8.84	3.75	9.85	8.06	9.89	2.8
	20	13.76	11.43	13.95		14.94	12.41	14.96	
4	0	8.81	7.37	8.71	3.76	9.76	7.98	9.82	2.78
	20	13.44	11.35	13.73		14.49	12.13	14.81	

Table 4.8: Average packet losses (threshold = -66 dBm, off = 0 dB).

Hyst (dB)	**Nº BE nodes**	**Average Packet Losses per Handover**							
		Ch1				**Ch2**			
		[65]	[70]	**Layer 2 IEEE 802.11**	**Our proposal**	[65]	[70]	**Layer 2 IEEE 802.11**	**Our proposal**
0	0	20	16	20	0.00034 (0.0067%)	22	18	22	0.00587 (0.084%)
	20	28	24	30		30	26	32	
2	0	18	14	18	0.00035 (0.0069%)	20	16	20	0.00588 (0.084%)
	20	28	22	28		30	24	30	
4	0	18	14	18	0.00034 (0.0068%)	20	16	20	0.00585 (0.084%)
	20	26	22	28		28	24	30	

First, given the structure of the used MAC scheme superframe, the transmission and reception of the frames required in [65] for the proposed scanning phase and the association and rescheduling phases required in [65], [70] are relegated to the BE period of the MAC scheme. In the same way, the transmission and reception of the frames required by Layer 2 IEEE 802.11 handover are relegated to the period dedicated to transmitting BE information. Hence, this increases the time required to execute the handover, which becomes even more evident when there are nodes trying to transmit the BE traffic during this period. These nodes will compete for access to the wireless medium with the nodes that want to execute a handover. Moreover, because the proposal in [70] uses a second IEEE 802.11 interface to evaluate the link quality of the neighbour APs, the decision whether to execute the handover or not can be taken faster than in [65] and in Layer 2 IEEE 802.11 handover. In these last two handover mechanisms, the link between the AP and the node that is associated with it can be deteriorated enough to require more control cycles to execute the handover process, and that is why the delay obtained in these cases are higher than the one obtained in [70].

On the one hand, regarding the packet losses, 100% of the RT frames sent during the execution of the handover are lost in [65], [70] and Layer 2 IEEE 802.11 handover algorithm because the communication is completely interrupted during the handover. On the other hand, packet losses are less than 0.1% with the soft-handover algorithm proposed in this chapter.

4.2.2.2 AP occupation

In addition to the average delay and the packet loss caused during the execution of the handover, the occupation level of each AP has been measured, i.e. how many wireless devices each AP has associated with it, on average. These results have been obtained only for the setups with the lowest percentage in terms of the average packet losses per handover (see Table 4.6). So, having an AP distribution and a mobility domain like the one shown in Figure 4.9, the occupation levels shown in Table 4.9 and Table 4.10 are obtained. The simulated network is composed of 3 APs, namely, AP0, AP1 and AP2 as shown in Figure 4.9.

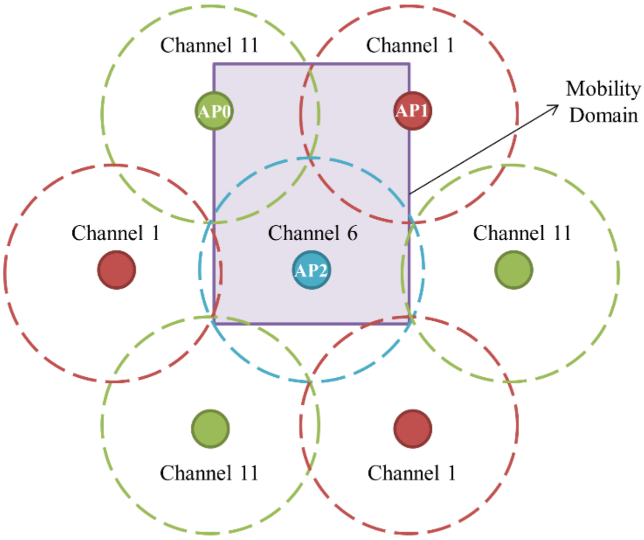


Figure 4.9: Simulated AP distribution and mobility domain.

The AP occupation is directly related to the number of handovers executed. Because in the simulation, the mobile devices move randomly through the defined mobility domain, there is more area under the AP2 coverage range so as it is shown in Table 4.9 and Table 4.10 at low threshold values (Condition I), the AP2 has more wireless nodes associated on average. In these cases, also fewer handovers occur as stated previously. In contrast, as the threshold value increases, and in consequence the number of handovers executed, the AP occupation is more balanced.

Table 4.9: Average AP occupation under channel 1.

Threshold	**Associated wireless nodes on average**		
	AP0	**AP1**	**AP2**
Condition I	2	2	16
Condition II	3	2	15
Condition III	5	3	12
Condition IV	5	5	10

Table 4.10: Average AP occupation under channel 2.

Threshold	**Associated wireless nodes on average**		
	AP0	**AP1**	**AP2**
Condition I	2	3	15
Condition II	3	3	14
Condition III	4	6	10
Condition IV	5	6	9

4.2.2.3 MAC to MAC delay

Finally, the MAC to MAC delay of the whole control cycle (comprises the transmission of both UL and DL traffic) has been calculated. The time that goes from the arrival of the UL packet in the node's MAC layer to the successful reception of the DL packet in the same node's MAC layer is considered as the whole control cycle MAC to MAC delay as seen in the Figure 4.10.

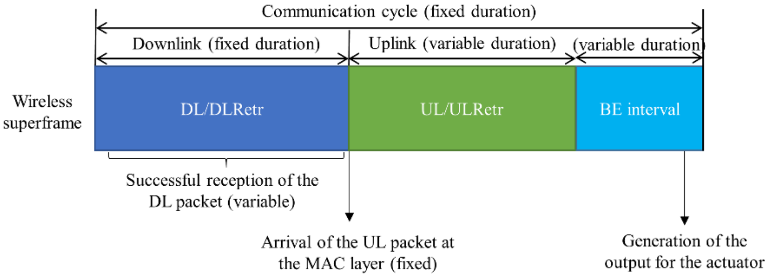


Figure 4.10: Definition of the MAC to MAC delay of the whole control cycle.

The results will be analysed by means of the CDFs of the MAC to MAC delay. The MAC to MAC delay has been evaluated only for the setups with the lowest percentage in terms of the average packet losses per handover (see Table 4.6). So, the results of the minimum, maximum and average MAC to MAC delay are shown in Figure 4.11 (Channel 1) and in Figure 4.12 (Channel 2).

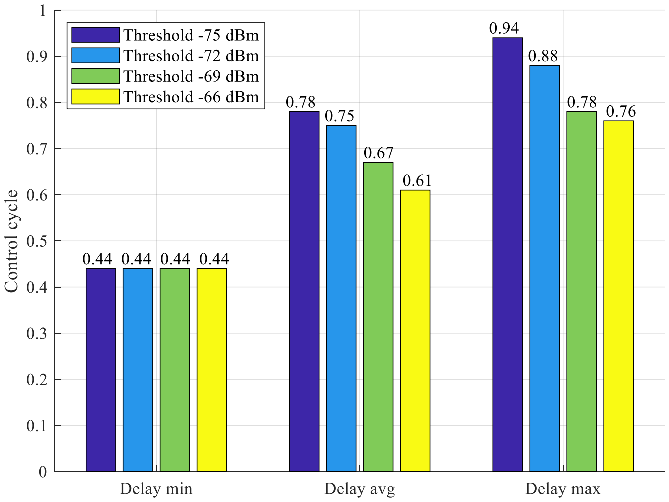


Figure 4.11: MAC to MAC delay under channel 1.

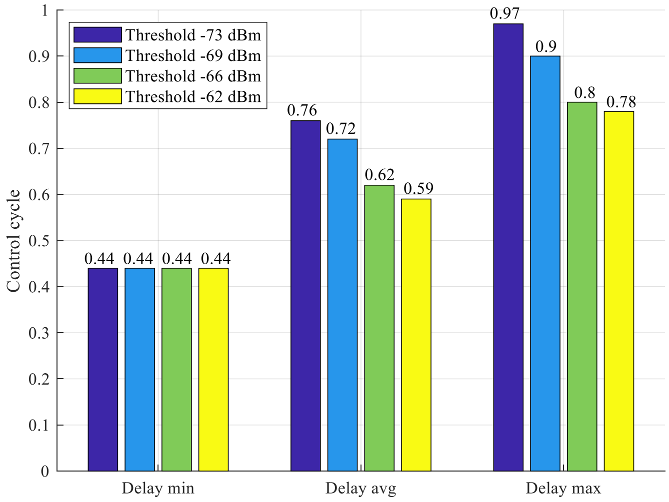


Figure 4.12: MAC to MAC delay under channel 2.

According to the results, for every setup, the calculated theoretical bounds in Section 3.2.1.2 match with the obtained MAC to MAC simulations. In none of the cases, the maximum MAC to MAC delay is greater than the theoretical bound, which corresponds to the length of the proposed superframe as stated in Section 3.2.1.2, i.e. the duration of the control cycle,. The 100% of the packets arrive at the receiver after waiting to access the medium—in the worst case, a maximum of 94% and 97% of the duration of one control cycle for channel 1 and channel 2, respectively.

Moreover, as concluded in Section 3.2.2.2, it is not relevant when the UL packet is received within the phase dedicated to transmitting the UL packets. Regardless of whether the UL packet is received in the first slot (dedicated to transmitting it) or in the last ULRetr slot, for the calculation of the MAC to MAC delay of the whole cycle, the full UL phase must be taken into account. In the same way, the BE interval must be taken also into account when evaluating the whole control cycle MAC to MAC delay. This time period is defined previously in (3.17) as $Offset_{DL}$.

Taking this into account, the minimum MAC to MAC delay is given in the case, in which a node receives its corresponding DL packet during the first slot dedicated to this purpose.

Finally, in the cases where there is a predominant AP associated with most of the nodes that form the network (Condition I), the obtained averaged MAC to MAC delay is higher. However, the delay is not only conditioned by the number of nodes associated with an AP, but also by the number of slots required to perform retransmissions.

4.3 Chapter summary

In this chapter, a soft-handover algorithm is proposed that guarantees an uninterrupted communication during the handover process without the need for a second radio interface like in other proposals and with a reduced growth in network overhead. The proposed handover algorithm is the main contribution of this chapter.

The proposed soft-handover algorithm is combined with the hybrid MAC scheme proposed in Chapter 3 in order to provide a reliable and deterministic communication demanded by the FA applications.

The proposed soft-handover algorithm proposes an AP selection logic based on a threshold and a comparison between the link quality levels of the APs is carried out. Moreover, in order to no interrupt the communication during the handover process, the device that has decided to carry out a handover to a target AP will momentarily have slots assigned in both APs.

The performance of the proposed soft-handover algorithm is compared with other handover algorithm proposed in some recent studies as well as the Layer 2 IEEE 802.11 handover in terms of average delay and RT packet losses during the handover process. The results show that the proposed soft-handover algorithm guarantees seamless communication during the handover process, unlike the other analysed handover algorithms. In the latter ones, 100% of the RT data packets sent during the execution of the handover were lost, because the communication between the AP/node was completely interrupted. On the contrary, with the proposed soft-handover algorithm, the communication between the AP/node is maintained during the whole handover process because the node will momentarily have slots in both the current and target APs. Moreover, it is shown that the obtained average delay during the handover execution and packet losses are very dependent on the selected handover parameters (hysteresis, offset and threshold values).

Finally, it is shown that the obtained average MAC-to-MAC is not only conditioned by the number of wireless devices associated with an AP, but it is also dependent on the number of slots required to perform retransmissions.

Chapter 5

Evaluation of STDMA protocol

In applications where the topology is changing continuously and a large number of devices are mobile such as those that require robots/drones to transport/handle material within manufacturing plants, centralized protocols are less suitable. In those centralized networks, APs are needed to coordinate access to the wireless medium, enabling predictable delays generally using TDMA-based MAC protocols. However, the need for an AP limits the flexibility of the application, entails an oversizing of the superframe (to ensure RT communication even in overload situations), involves high control cycles and requires more complex handover algorithms as the number of wireless devices increases.

In order to overcome those challenges, distributed networks or ad-hoc networks can be considered as promising alternatives to the centralized protocols commonly used in FA, like the one proposed in Chapter 3. One of the most promising distributed network approaches is STDMA [89] protocol that is already in commercial use and mandatory for all ships over a certain size and has also been evaluated for future inter-vehicle communication networks [106], [107]. Therefore, given its self-organization ability, STDMA is studied in this chapter as an alternative to carrying out a handover without centralized systems in FA applications. By means of STDMA, it is possible to cope with the changes in the topology dynamically offering great flexibility to the system and allows the use of the system by a large number of devices. Thanks to the flexibility offered by the STDMA algorithm, devices with different control cycles (if all packets adhere to a fixed maximum size) or static/mobile devices (with different speeds) can coexist in the same network.

Although there are several papers in the literature that have evaluated deeply the STDMA protocol for vehicular networks [108]–[114], those works have mainly focused on the comparison of the performance of STDMA with CSMA/CA under vehicular environment, without taking into account neither multipath dispersive channels nor Doppler spread. Therefore, an evaluation of the STDMA protocol under a multipath dispersive time-variant industrial channel is carried out to see the suitability of this protocol for industrial applications.

The first section of this chapter describes each of the phases of the STDMA protocol as well as its configuration parameters. In Section 5.2, the simulation and setup the results obtained through OMNeT++ simulations in combination with VEINS framework are presented. The simulation setup include the description of the considered scenarios for a single and multiple STDMA network, the selected STDMA configuration parameters and the evaluated metrics. Finally, Section 5.3 states the conclusions drawn from the evaluation of STDMA protocol.

5.1 STDMA protocol description

STDMA was originally conceived for the Automatic Identification System (AIS) [115] used in the naval industry. By means of STDMA, all commercial boats share their location and relevant information with other boats within their range. More recently, STDMA has been proposed for handling safety applications in vehicular networks since it can solve overload situations and a large number of simultaneous devices.

STDMA employs a TDMA-based approach in which time is divided into frames of a predefined duration, which in turn, is divided into fixed-length slots which will be used to carry out the transmissions. In each slot, a single packet can be transmitted. For the proper operation of the STDMA protocol, each packet transmitted by a node must contain a timeout, an offset and the position of the transmitting node. These are used to define the duration of a slot assignment and to the interval between consecutive transmissions, respectively. Moreover, each node must know when slots begin and end. For that, a global satellite navigation system such as Global Positioning System (GPS) or Galileo is needed.

The nodes themselves determine their own transmission slots based on the information received from other nodes. The used medium access strategy in STDMA is based on a slot reservation process, which is divided into four phases: initialization, network entry, first frame and continuous operation. All these phases are briefly described below. To help to understand the description of each phase, the configuration parameters of STDMA have been defined in Table 5.1. For a more detailed explanation of the STDMA protocol, please refer to [89].

Table 5.1: Configuration parameter of STDMA.

Parameter	**Description**	**Value**
Report rate (R_r)	Transmitting packets per frame	Selected by configuration
Nominal Transmission Slot (s_{NTS})	Slot chosen to carry out a transmission	Randomly calculated
Nominal Start Slot (s_{NSS})	Slot used by a device to announce itself to the network	$s_{NSS} = [0, s_{NI}]$
Nominal Slot (s_{NS})	Central slot of the slots selected for transmission	$s_{NS} = s_{NSS} + (k * s_{NI})$ k from 0 to R_r -1
Nominal Increment (s_{NI})	Average distance (in slots) between two consecutive transmissions	$s_{NI} = \left\lfloor \frac{slots\ per\ frame}{R_r} \right\rfloor$
Selection Interval Ratio (R_{SI})	Relationship between the width of the s_{NI} and the s_{SI}	Selected by configuration
Selection Interval (s_{SI})	Candidates slots to carry out the transmission	$s_{SI} = (2*(\lfloor 0.5*(s_{NI}-1)*R_{SI} \rfloor)) + 1$
Timeout (*ni*)	Duration of a slot assignment (in frames)	Uniform distribution [*ni* min, *ni* max]
Network Entry Duration ($networkEntry_{dur}$)	Max. duration of the network entry	Selected by configuration

5.1.1 Initialization phase

During the initialization phase (shown in Figure 5.1), each node that wants to join the STDMA network has to listen to the wireless medium for the duration of one frame. Thanks to this mechanism, the node knows which slots are being used by the rest of the nodes within its range and will be able to create an internal map of the STDMA frame, which will be continuously updated in the other phases of the protocol.

The beginning of the initialization phase does not necessarily have to coincide with the beginning of the global STDMA frame. The starting point of this phase will be given by the instant at which the node wants to be part of the network.

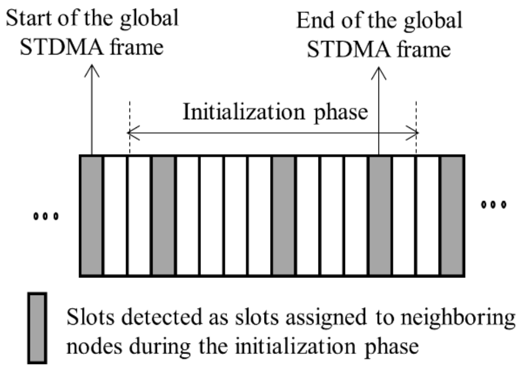


Figure 5.1: The initialization phase of STDMA.

5.1.2 *Network entry phase*

After the initialization phase elapses, the node enters the network entry phase. The main objective of this phase is to announce the node to the STDMA network. For that, a set of slots that follow the last slot of the initialization phase are going to be considered as candidate slots to transmit the packet with which the node will be announced to the network. This set of slots will be bounded by the parameter $networkEntry_{dur}$. Among the considered slots set, the selected slot to transmit the Network Entry Packet (NEP) is going to be randomly chosen according to the probability persistent (p-persistent) algorithm of the Random Access TDMA (RATDMA) protocol [89]. The algorithm is based on the following principles:

1) When a slot is selected within an s_{SI}, it is randomly selected among all slots within the s_{SI} which are perceived as free,
2) A slot is perceived as free when no node was using it in a previous frame or when a node was using it in the previous frame but the timeout was 0 and when no node has indicated that they will use it by stating that its offset from a previous slot was equal to this slot and
3) If no slots are free, an occupied slot will deliberately be selected, and the selection is made based on which node that is located furthest away.

In addition to selecting the slot in which the node announces itself to the network, it must determine parameters like s_{NI}, s_{NSS} and s_{SI} in order to decide in which future slot it will perform its first transmission (s_{NTS}). The corresponding timeout and offset values of the selected s_{NTS} will be included in the packet transmitted to announce the node to the network. So, each node collects information about the state of all slots, not just in the current frame but also in the next frame and in the slots soon to come by checking if the slot is used, for how long it will be used, and which is the next slot (offset) to be used. Figure 5.2 shows the relation between the STDMA configuration parameters s_{SI}, s_{NI}, s_{NSS} and s_{NTS}.

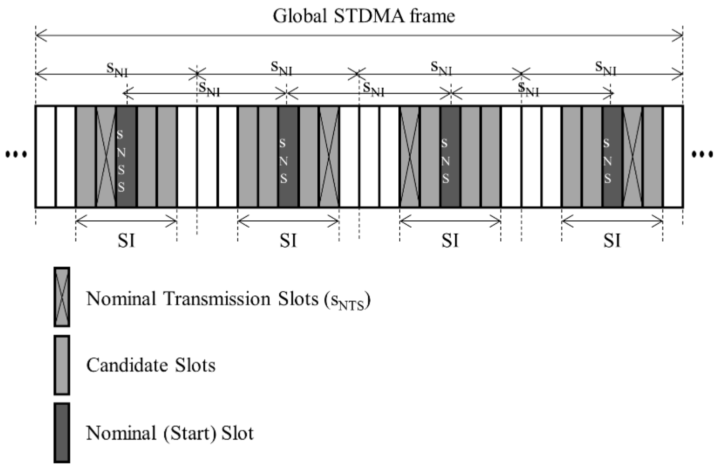


Figure 5.2: Diagram showing the configuration parameters s_{SI}, s_{NI}, s_{NSS} and s_{NTS}.

5.1.3 First frame phase

The main task of this phase is to allocate the remaining required slots to achieve the predefined R_r parameter. As in the network entry phase, those slots will have a corresponding timeout and offset. During this phase, the node will transmit packets in the slots that have been selected. When the last scheduled packet is transmitted within this first frame, the offset of this packet is set to zero to indicate that no more allocations will be made. By sending this last packet, the node will enter the last phase of the STDMA protocol. Figure 5.3 shows a simple example of the network entry and first frame phases. In this example, only 2 packets are required to be transmitted per frame ($R_r = 2$).

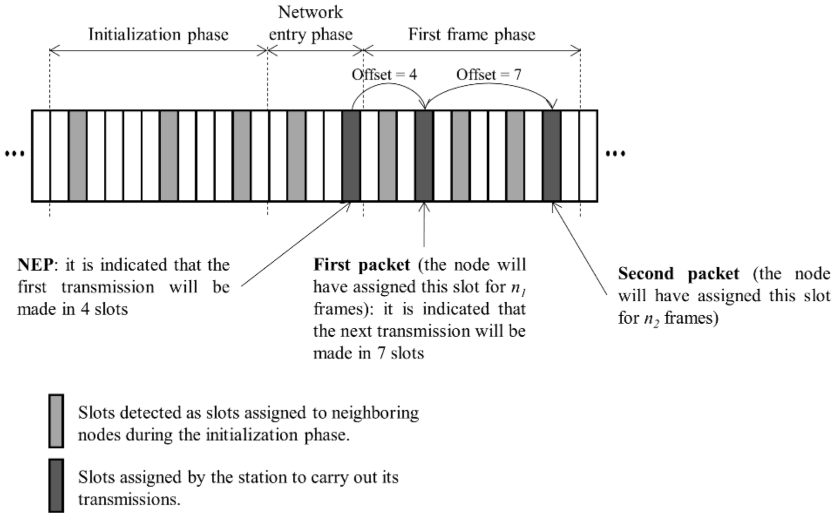


Figure 5.3: Example of the Network entry and First frame phases.

5.1.4 Continuous operation phase

More than two frames are needed to reach the continuous operation phase. Nevertheless, at this phase, the other nodes of the STDMA network know the slot reservation pattern of the newly arrived node. The main task of this phase is to transmit a new packet every time an s_{NTS} is reached and to reduce the time value by one unit each time a slot is used. This phase is also responsible for performing a re-allocation of slots every time the internal timeout of an assigned slot expires.

5.1.5 *Packet collisions*

Note that slot allocation collisions can occur in STDMA. The following are the main causes that can lead to packets collisions:

1) The whole set of slots considered as candidate slots to transmit the NEP during the network entry phase are busy or assigned to other nodes. In this case, an occupied slot will deliberately be selected by the entering node and the selection is made based on which node that is located furthest away.
2) Two (or more) nodes can randomly select the same slot to transmit the NEP during the network entry phase.
3) During the first frame or continuous operation phase, in order to satisfy the minimum candidate slots requirement, a slot assigned to other node is considered and this slot is selected to perform a transmission.
4) During the first frame or continuous operation phase, two (or more) nodes that are hidden from each other can use the same slot to perform a transmission believing that it is not being used by another node. However, a third node that can communicate with both other nodes, will not be able to receive correctly their transmissions since they collide.

5.2 Performance evaluation

5.2.1 *Evaluated scenarios for a single STDMA network*

There are a multitude of STDMA protocol parameters which can be varied, such as the number of transmissions that a device performs in a frame (R_r), the load of the network, the minimum candidate slot, the R_{SI}, etc. These parameters will influence to a greater or lesser extent the performance of STDMA. Moreover, the channel model used has a great influence on the performance of the protocol. That is why four different scenarios have been considered for the evaluation of the STDMA protocol in a single STDMA network. Each simulated scenario focuses on a different aspect. The first scenario focuses on evaluating the performance of STDMA protocol under ideal conditions, the second scenario focuses on determining the influence of the introduction of an industrial channel, the third scenario focuses on determining the influence of a fixed doppler shift and the fourth scenario focuses on determining the influence of a variable doppler shift.

5.2.1.1 Scenario 1: Perfect communication conditions

To evaluate the influence of the STDMA parameters on the overall performance of the network, perfect communication conditions are considered in this scenario, i.e. all stations can successfully decode each other’s transmissions as long as there is no interference. In this scenario, mobility is not considered either of the nodes or the environment. So, all the nodes are static and therefore there is no Doppler shift. Moreover, nodes are randomly placed in a predefined area as shown in Figure 5.4 (the maximum relative distance between a transmitter and a receiver will correspond to a free-space loss of -85 dB). Finally, the obtained results are collected from all the nodes that are placed in the defined predefined area.

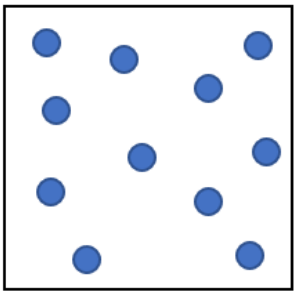


Figure 5.4: Proposed single STDMA networks scenario.

5.2.1.2 Scenario 2: Industrial channel conditions

To evaluate the performance of the STDMA protocol under more realistic conditions, in this scenario a multipath dispersive time-variant industrial channel is considered. The selected channel is the one defined as Ch1 in Section 4.2.1.1. As in Scenario 1, mobility is not considered. Moreover, nodes are randomly placed in a predefined area as shown in Figure 5.4 (the maximum relative distance between a transmitter and a receiver will correspond to a free-space loss of -85 dB). Finally, as in the previous scenario, the obtained results are collected from all the nodes that are place in the defined predefined area.

5.2.1.3 Scenario 3: Fixed Doppler conditions

In this scenario, besides taking into account the industrial channel considered in Scenario 2, a fixed Doppler shift is also considered. Although the nodes are static, a fixed Doppler shift relative to 30 km/h is considered in order to simulate the Doppler shift caused by the movement of the surrounding nodes. A speed of 30 km/h has been set because it is the maximum speed considered in most critical industrial applications [10].

In order to evaluate the influence of a fixed Doppler shift, three different setups have been considered in which the transmitters are always at the same distance from the receivers. This allows getting results based on the relative distance. The considered setups are:

- Setup 3.A: the relative distance between the transmitters and the receivers is always the same and corresponds to a free-space loss of -70 dB.
- Setup 3.B: the relative distance between the transmitters and the receivers is always the same and corresponds to a free-space loss of -75 dB.
- Setup 3.C: the relative distance between the transmitters and the receivers is always the same and corresponds to a free-space loss of -80 dB.

Finally, as in previous scenarios, the obtained results are collected from all the nodes.

5.2.1.4 Scenario 4: Variable Doppler conditions

In this scenario, besides taking into account the industrial channel considered in Scenario 2 and 3, a variable Doppler shift is also considered. As in Scenario 1 and 2, nodes are randomly placed in a predefined area as shown in Figure 5.4 (the maximum relative distance between a transmitter and a receiver will correspond to a free-space loss of -85 dB). In order to evaluate the influence of a variable Doppler shift, two different setups have been considered:

- Setup 4.A: One node is moving at a constant speed of 30 km/h through the predefined area and it follows a random movement pattern. The rest of the nodes are static.
- Setup 4.B: All the nodes are mobile. They are moving at a constant speed of 30 km/h through the predefined area and they follow a random movement pattern.

In the case of Setup 4.A, the obtained results are collected from the node that is moving, whereas in the case of Setup 4.B, results are collected from all the nodes that are placed in the defined predefined area.

Moreover, in the case of Setup 4.A, the relative speed between the nodes varies between 0 km/h and 30 km/h, whereas in the case of Setup 4.B, the relative speed between the nodes ranges from 30 km/h (considered as the minimum Doppler shift caused by the movement of the surrounding nodes) to 60 km/h (twice the considered maximum speed). So, taking the minimum and the maximum speeds (V) and a transmission frequency (f_{tx}) of 2.412 GHz, there will be a variable Doppler shift (Δf) which is defined as

$$\Delta f = f_{tx}\,\frac{V}{c}. \tag{5.1}$$

Where c is the speed of light. Δf ranges from 0 Hz to 67.046 Hz in the case of Setup 4.A and between 67.046 Hz and 134.092 Hz in the case of Setup 4.B.

So, since a varying Doppler shift is considered in this scenarios, unlike in Section 4.2.1.1, the channel attenuation vectors have been generated considering the maximum Doppler shift defined in 134.092 Hz.

5.2.2 Evaluated scenarios for a multiple STDMA network

A scenario in which a node traverses two independent STDMA networks has been considered in order to obtain individual statistics of the traversing node. It will be analysed how the incorporation into a previously formed STDMA network of a node that knows the slot assignment of a different STDMA network is managed. This traversing node will be continuously crossing from one STDMA network to the next in a straight line and traversing them through the central point of the predefined area of each of the simulated STDMA networks (see Figure 5.5). The STDMA networks will be separated so that they do not interfere with each other.

In this scenario, both the industrial channel defined as Ch1 in Section 4.2.1.1 and a variable Doppler shift are considered. Nodes are randomly placed in a predefined area (the maximum relative distance between a transmitter and a receiver will correspond to a free-space loss of -85 dB). Moreover, all the nodes are mobile. They are moving at a constant speed through the predefined area and they follow a random movement pattern.

Finally, in this scenario, the statistics have been obtained based on the relative distance between the traversing node and the rest of transmitting nodes and. It has been considered that the closest nodes to the traversing node are most important and thus it is better to collide with a more distant one or to lose a packet sent by a more distant node. So, 3 different coverage areas have been considered:

- Setup A: A coverage area in which only the transmitters whose free-space losses are > -70 dB with respect to the traversing node are considered.
- Setup B: A coverage area in which only the transmitters whose free-space losses are > -75 dB with respect to the traversing node are considered.
- Setup C: A coverage area in which only the transmitters whose free-space losses are > -80 dB with respect to the traversing node are considered.

Depending on the considered coverage area, there will be cases in which when the traversing node is just in the intermediate point of the two STDMA networks it will not be part of either network A or B (Setup A and B). In contrast, when the traversing node is just in the intermediate point of the two networks STDMA, it will be part of both networks (Setup C).

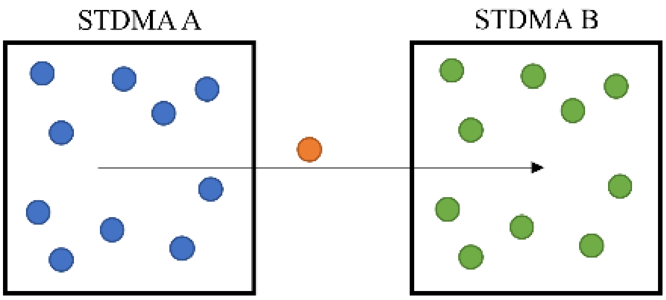


Figure 5.5: Proposed multiple STDMA networks scenario.

5.2.3 *Channel attenuation with variable Doppler shift*

As stated in Section 4.2.1.1, different vectors have been generated to model a temporal variation of the small-scale attenuation of the channel, which is computed for a maximum Doppler frequency that corresponds to twice the maximum speed of the nodes. However, the Doppler shift between two nodes in movement will not always be the same, since as they have a random movement pattern, the relative speed between them will vary continuously. This will result in variations in the Doppler shift and will in turn affect how rapidly the channel changes. This effect can be observed in Figure 5.6 and Figure 5.7.

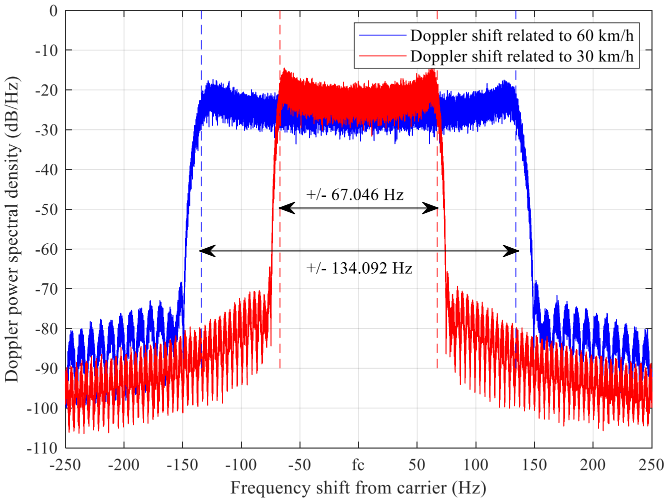


Figure 5.6: Doppler power spectrum density of the modelled industrial channel.

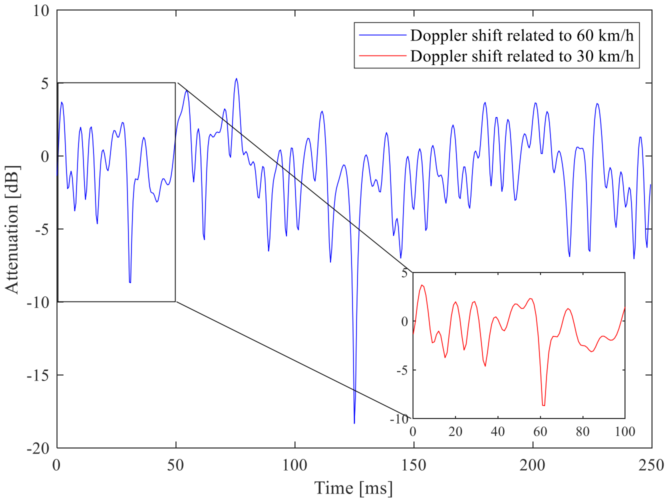


Figure 5.7: Variation in the small-scale attenuation of the modelled industrial channel.

In Figure 5.6, the obtained Doppler power spectrum density of the modelled industrial channel is shown for the considered minimum and maximum Doppler shifts. In the figure, the maximum shift that the transmission frequency can suffer due to the Doppler effect is shown. As can be seen, the greater the relative speed between the transmitter and the receiver, the greater the frequency shift becomes.

In contrast, Figure 5.7 shows an example of the resulted variation in the small-scale attenuation of a signal after passing through the considered industrial channel with the considered maximum and minimum Doppler shift. Depending on the relative speed between the transmitting and receiving nodes, the attenuation of the channel will vary differently, being the variation slow when the relative speed is reduced.

5.2.3.1 Calculation of the Doppler shift

The Doppler shift describes the frequency shift perceived by a receiver when the transmitter and the receiver are moving relative to one another. When in a scenario like the one proposed in Section 5.2.1.4, where the movement pattern of the nodes is random, not only the relative speed between the nodes must be taken into account. The angle between the relative speeds must also be considered. Therefore, the process to calculate the Doppler shift regardless of the direction in which the nodes move is described below.

First, it is necessary to know both the position (P) and the speed (V) of the transmitting (P_{Tx}, V_{Tx}) and the receiving (P_{Rx}, V_{Rx}) node, both on the x and y axes. Then it is necessary to calculate both the relative velocity vector ($\overline{AV}$) and the relative position vector ($\overline{x}$). To make these calculations, Equations (5.2) and (5.3) will be used. It will also be necessary to calculate the relative velocity vector module ($|\overline{AV}|$) and the relative position vector module ($|\overline{x}|$), after which the cosine of the angle between the relative speeds (θ) is calculated (5.4). Angle θ corresponds to the existing angle between $\overline{AV}$ and $\overline{x}$. Finally, the Doppler shift (Δf) is calculated as expressed in Equation (5.5), where f_{tx} corresponds to the transmission frequency and c corresponds to the speed of the light.

$$\overline{AV} = V_{Tx} - V_{Rx} = \left(V_{x1} - V_{x2},\ V_{y1} - V_{y2}\right) = \left(V_{x_{tot}},\ V_{y_{tot}}\right). \tag{5.2}$$

$$\overline{x} = P_{Rx} - P_{Tx} = \left(P_{x2} - P_{x1},\ P_{y2} - P_{y1}\right) = \left(P_{x_{tot}},\ P_{y_{tot}}\right). \tag{5.3}$$

$$cos\,\theta = \frac{\overline{x} \cdot \overline{AV}}{|\overline{x}| \cdot |\overline{AV}|}. \tag{5.4}$$

$$\Delta f = f_{tx} \cdot \frac{/\overline{AV}/}{c} \cdot cos\,\theta. \tag{5.5}$$

5.2.4 Simulated parameters

The described scenarios focus on the evaluation of the performance of STDMA in industrial environments, whose requirements in terms of reliability and determinism tend to be more restrictive than in vehicular scenarios as stated in Chapter 2. Given that both the transmission cycles and the amount of data to be transmitted per packet are smaller in control industrial applications than in vehicular safety applications, the duration of the STDMA frame has been shortened in the simulations. Considering an IEEE 802.11g physical layer with a data rate of 24 Mbps, 20 MHz of bandwidth and 60-bytes packets (including all protocol overhead), the STDMA frame will consist of 1694 slots with a total frame duration of 100 ms. We use an IEEE 802.11 physical layer due to the increasing interest in the use of this standard in industrial applications [96]. The IEEE 802.11g physical layer has also been chosen because, when no

MIMO approach is used due to the introduced overhead, there are no significant advantages between using the physical layer of IEEE 802.11g or the physical layers of the most recent amendments of the IEEE 802.11 family [102], [103].In contrast, a data rate of 24 Mbps has been selected because the slower rates are too slow, thus increasing the delay of the packets, and the faster rates are affected by the fading more, thus suffering from higher losses.

Table 5.2 and Table 5.3 summarize the selected configuration of the STDMA protocol for all the considered scenarios and the needed nodes for a specific network load, respectively. The network load has been defined as the percentage of slots used in a frame in the case in which all nodes of the STDMA network transmit without sharing a slot.

It must be noted that, since some collisions can be avoided by reducing the minimum candidate slots to one, this will be the value used in the following evaluations. Moreover, a reduced s_{SI} allows getting a reduced jitter at the expense of increasing the probability of collisions between simultaneous transmissions. In the same way, with a high s_{SI}, the jitter increases while the probability of collisions is lower. So, for these simulations, an intermediate value of R_{SI} has been selected.

Table 5.2: Selected configuration parameters of STDMA.

Parameter	**Value**	
	Single STDMA scenarios	**Multiple STDMA scenarios**
Min. number of candidate slots	1 slot	
Reservation timeout	3 frames – 7 frames	1 frame – 4 frames 2 frames – 5 frames 3 frames – 7 frames
Max. Duration of network entry	150 slots	
R_{SI}	60%	
R_r	10 and 20 packets per frame	10 packets per frame
Initialization of the nodes	Progressive initialization	
Network load	25%, 50% and 99%	25% in each STDMA network
Physical layer	IEEE 802.11g	
Data rate	24 Mbps	
Noise threshold	-90 dBm	
Transmission power	Fixed	
Frame duration	100 ms (1694 slots)	
Packet size	60 bytes	
Speed of the nodes	Depends on the setup	30 km/h 3.6 km/h

Table 5.3: Number of nodes for a specific network load.

R_r	**Network load (for an STDMA frame of 1694 slots)**	**Nodes**
10	25%	43
	50%	85
	99%	168
20	25%	22
	50%	43
	99%	84

5.2.5 Evaluated performance metrics

To evaluate the requirements on delay, reliability, fairness and scalability, several performance metrics have been selected.

5.2.5.1 Channel access delay

The channel access delay corresponds to the time elapsed from when the MAC layer of the transmitter receives the packet until it is transmitted through the channel. This parameter highlights the ability of the MAC to provide a predictable delay. The minimum and maximum channel access delay are measured.

5.2.5.2 Slot occupation distribution (SOD)

SOD describes the probability of a slot being free, assigned to one node or to several nodes. That is, SOD characterizes how many nodes are reusing the same slot. Both the collision probability and the maximum number of nodes using the same slot are measured.

5.2.5.3 Packet Error Rate (PER)

When all the nodes can successfully decode other nodes’ transmissions as long as there is no interference, packet losses will only be due to collisions that may occur between two simultaneous transmissions. However, when industrial channel conditions are considered, packet losses are not only due to possible collisions but can also be due to effects such as fading.

In the case of single STDMA network scenarios, the averaged total packet error considering both errors due to channel and due to collisions is measured. In contrast, in the case of multiple STDMA networks, the distribution of the packet losses due to collision and the distribution of the packet losses due to the channel are measured.

5.2.5.4 Packet Inter-Arrival Time (PIAT)

Ideally, the PIAT is equal to the time between two transmissions of the same transmitter node, i.e. the reciprocal of the R_r value. However, due to how the STDMA protocol schedules the packet in time, which depends on the selected slot in the s_{SI}, there will be a jitter, i.e., a margin around the packet transmitting time that ceases to be periodic. Moreover, it allows evaluating if the packet losses are distributed equally or follow each other, i.e. they belong to two nodes using the same slot repeatedly. Note that both the PER and the PIAT are related since the PER measures the percentage of erroneous packets and the PIAT established if the packet losses are evenly distributed or consecutive. In this way, it is more desirable for the same PER value to have a reduced PIAT.

The CDFs for the PIAT in different ranges of interest are measured. The considered ranges of interest are when only the transmitters whose free-space losses are > -70 dB respect to the receiver are considered, when only the transmitters whose free-space losses are > -75 dB respect to the receiver are considered and when only the transmitters whose free-space losses are > -80 dB respect to the receiver are considered. Those ranges of interest correspond to the coverage area considered when defining the Scenarios for multiple STDMA network in Section 5.2.2.

Moreover, from the CDFs, the percentage in which no packets are lost between two successful receptions, the percentage in which one packet is lost between two successful receptions, the percentage in which more than one packets are lost between two successful receptions and how many packets are lost at most between two successful receptions are measured.

5.2.6 *Simulation results of the single STDMA network scenarios*

This section presents and discusses the results obtained from the simulation-based evaluation of STDMA under the single STDMA scenarios described in Section 5.2.1. The evaluation of the STDMA protocol has been carried out through OMNeT++ simulator in combination with VEINS [116] in order to have a mobility framework. To minimize any randomness in the results, each evaluation has been performed using several seeds.

5.2.6.1 Channel access delay

The traffic generation has been scheduled so that a new packet is generated just at the start of each new s_{SI}. Therefore, the channel access delay is predictable, and its maximum will be defined by the duration of the Selection Interval (d_{SI}) (5.6).

$$d_{SI} = (s_{SI} - 1). \tag{5.6}$$

The minimum channel access delay will be 0 seconds, i.e. the slot selected to carry out a new transmission is the first slot of s_{SI}. Thus, knowing that the maximum channel access delay is defined by d_{SI}, it will only be affected by the number of slots in a frame, R_r and R_{SI}. In Table 5.4 an overview of the maximum channel access delay values obtained for different combinations of R_{SI} and R_r can be observed.

Table 5.4: Maximum channel access delay.

R_{SI}	**R_r**	**For an STDMA frame of 1694 slots**		
		s_{NI}	**s_{SI}**	**SI duration = Max delay (in slots)**
20%	10	169	33	32
40%			67	66
60%			101	100
80%			135	134
100%			169	168
20%	20	84	17	16
40%			33	32
60%			49	48
80%			67	66
100%			83	82

It can be concluded that neither the simulated channel nor the mobility or how the nodes enter the STDMA network affect the maximum channel access delay since it will depend solely on d_{SI}.

Note that if the creation of the packet is not right at the beginning of the s_{SI}, the STDMA protocol continues guaranteeing that the transmission of the packet will be done before this period ends. So, in this case, the maximum time interval from the generation of the packet to the beginning of the next s_{SI} shall be added to the d_{SI} to obtain the maximum channel access delay.

5.2.6.2 Slot occupation distribution (SOD)

The following figures show on the one hand, the probability that a slot is assigned to two or more nodes, i.e. the probability of collisions between simultaneous transmissions (denoted as Collision probability). In the other hand, the figures show the maximum of nodes that can be used the same slot. Figure 5.8 shows the results for a network load of 25%, Figure 5.9 shows the results for a network load of 50% and Figure 5.10 shows the results for a network load of 99%.

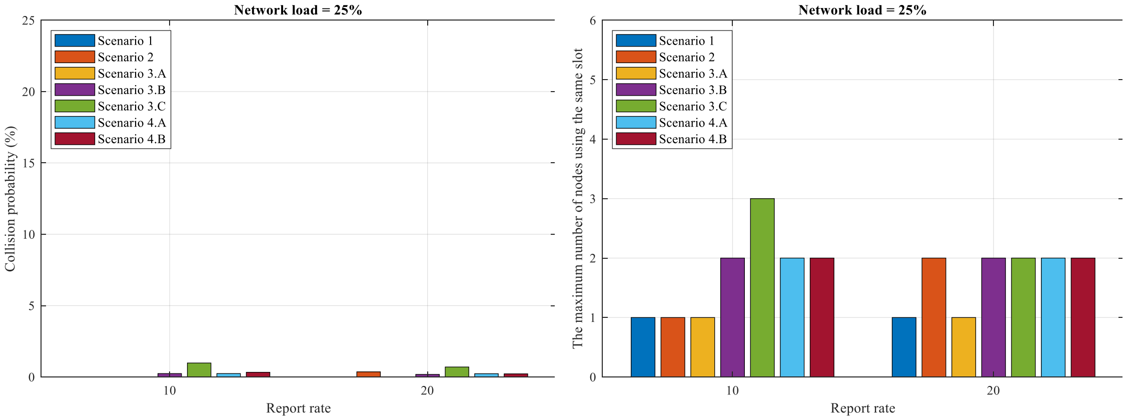


Figure 5.8: Collision probability and number of nodes using the same slot (Load of 25%).

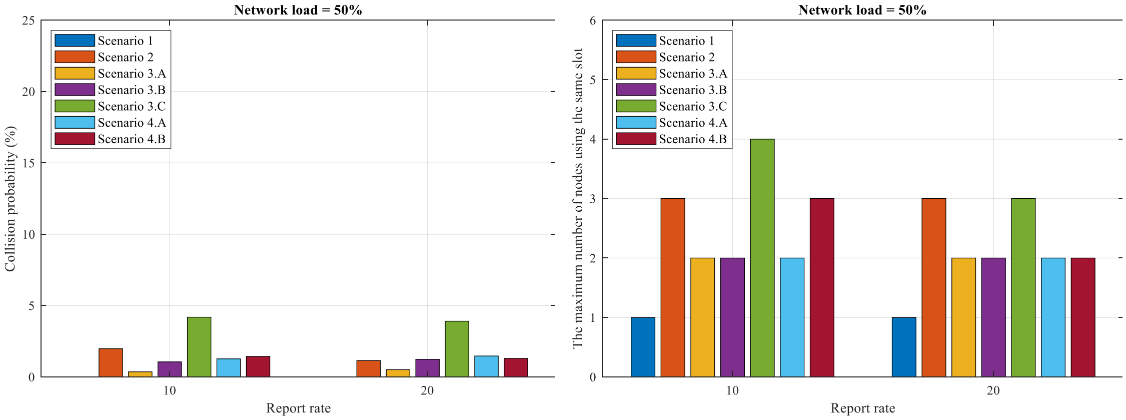


Figure 5.9: Collision probability and number of nodes using the same slot (Load of 50%).

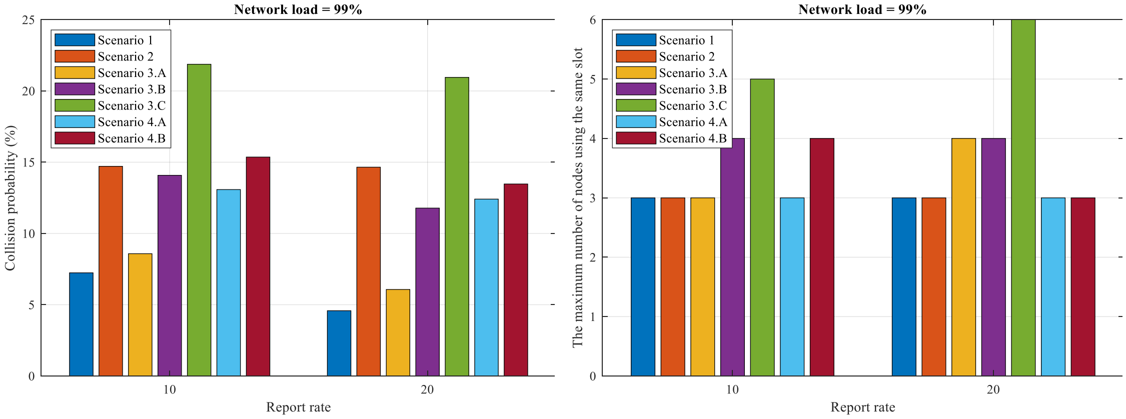


Figure 5.10: Collision probability and number of nodes using the same slot (Load of 99%).

Obtained conclusions regarding the network load

As the load of the network increases (having the same R_r value), the probability that a node must reuse a slot that is assigned to a neighbouring node grows. This is because there are more nodes that must choose a slot in which to transmit. It also increases the probability that more nodes must share the same slot. For example, when the network load is 25%, in the worst case there are three nodes at most that share the same slot. However, when the network load is 99%, there are up to six nodes that share the same slot in the worst case.

Obtained conclusions regarding the *Rr*

Generally, regardless of the evaluated scenario, as R_r increases, the probability that a node can occupy a slot that is already assigned to another node decreases. This is because there are also fewer nodes that must compete to use the slots.

Obtained conclusions regarding the simulated scenario

Taking into account the scenario in which perfect communication conditions are considered (Scenario 1), there are not collisions when the network load is 50% or less. Since the nodes are entering the network in a progressive way, this allows the nodes to be aware of the slots occupied by the neighbouring nodes and discard them to carry out their transmissions. However, due to the way in which slot allocation is made in STDMA, despite a perfect communication conditions are considered in Scenario 1, when the network load is 99% a slot allocation collisions can occur as shown in Figure 5.10. In this case up to three nodes can use the same node with a collision probability of 7.24% when an $R_r = 10$ and with a collision probability of 4.58 % when an $R_r = 20$ is considered.

In contrast, despite the progressive initialization of the nodes, when an industrial channel is considered, the probability that two or more nodes use the same slots is not zero in almost all the cases when the load is below 50% as it happens when perfect communication conditions are considered. Despite this, the probability of collision even using industrial channels and/or Doppler shift, is less than 5% in all cases in which the load is 50% or less.

Among all the scenarios in which industrial channels are considered (Scenario 2 to 4), the one who shows the worst performance is the Scenario 3.C in all the cases. This is because the transmitters are always at the same relative distance respect to the receivers that correspond to a free-space loss of -80 dB. In the other scenarios, either by the random position in which the static nodes have been placed or by the movement of the nodes themselves, the channel conditions are not so harmful so the slot allocation in STDMA is made from in a more effective way avoiding potential collisions (among other things because the nodes have a better knowledge of the state of the slots).

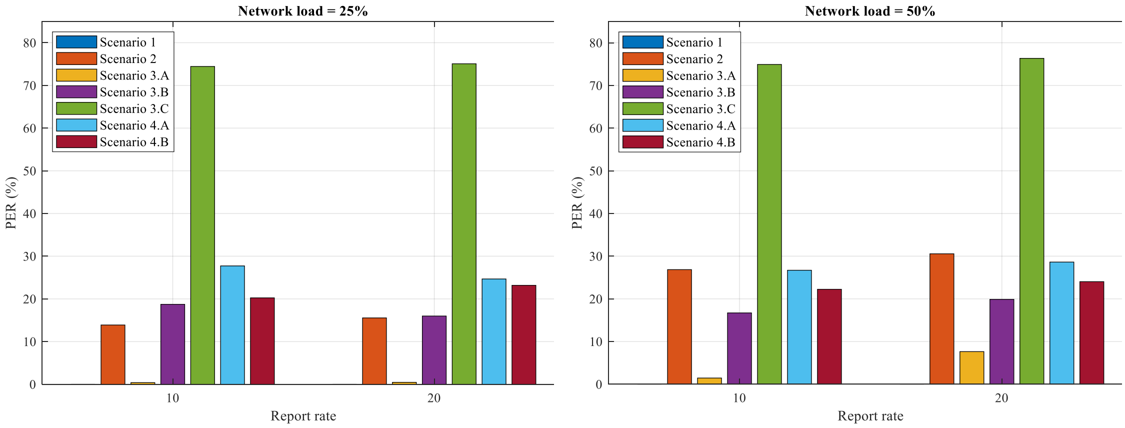
In contrast, the results of the Scenario 3.A are the best among the scenarios that consider industrial channels and it is due just for the opposite reason. Despite the Doppler shift, given that in this Scenario the transmitters are always at the same relative distance respect to the receivers that correspond to a free-space loss of -70 dB, the performance of STDMA resembles to the performance the STDMA in Scenario 1. For example, in Scenario 3.A for a network load of 99%, the collision probability is 8.58% when an $R_r = 10$ and the collision probability of 6.07 % when an $R_r = 20$ is considered. In contrast, in Scenario 2, where no Doppler shift is considered but the nodes are randomly placed in a predefined area, for a network load of 99%, the collision probability is 14.71% when an $R_r = 10$ and the collision probability of 14.65 % when an $R_r = 20$ is considered.

Finally, comparing the cases in which a variable Doppler shift is considered (Scenarios 4.A and 4.B), it is shown how the scenario with the biggest variation in the Doppler shift (Scenario 4.B) shows the worst performance. This is because, in this scenario, there is not only one mobile node, all the nodes in the network are moving so it is easier to collide.

5.2.6.3 Packet Error Rate (PER)

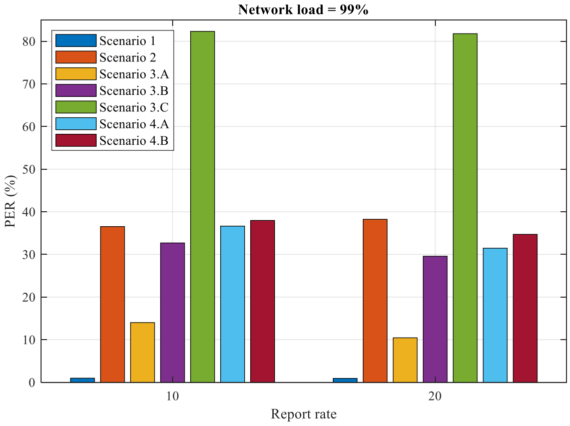
Figure 5.11 show the PER for a network load of 25%, 50% and 99%. As can be seen, there is a great difference, especially when the load is greater than 50%, between evaluating the performance of the STDMA protocol in a scenario with perfect communication conditions

(Scenario 1) and considering industrial channels (Scenario 2 to 4). It should be noted that, when a perfect communication condition is considered, packet losses will only be due to collisions that may occur between two simultaneous transmissions. In contrast, when simulating industrial channel conditions, the packet losses are not only due to possible collisions, but the channel itself can cause packet losses due to effects such as fading.



(a) Network load of 25%

(b) Network load of 50%



(c) Network load of 99%

Figure 5.11: Packet error rate.

As stated in the obtained SOD results, as the network load increases, more packets are lost due to collisions between transmissions. If Scenario 1 is considered, only when the network load is 99% a few packets are lost. Specifically, the PER is 0.97% when $R_r = 10$ and 0.92% when $R_r = 20$.

As when analysing the results related to SOD, among all the scenarios in which industrial channels are considered (Scenario 2 to 4), the one who shows the worst performance is the Scenario 3.C in all the cases due to the same reason. In this Scenario when the network load is 50% or less the PER is around 75% and when the network is 99% the obtained PER is around 80%.

Moreover, as in SOD, the results of the Scenario 3.A are the best among the scenarios that consider industrial channels. Nevertheless, in this case, the packet losses are much higher than in Scenario 1.

Finally, comparing the cases in which a variable Doppler shift is considered (Scenarios 4.A and 4.B), it is shown how the scenario with the biggest variation in the Doppler shift (Scenario 4.B) only shows the worst performance when the network load is 99%. This is because in this case, the difference between collision probability of both scenarios is bigger than in lower network load cases, so it affects more to the obtained PER.

5.2.6.4 Packet Inter-Arrival Time (PIAT)

The possible minimum PIAT value can be obtained taking into account the s_{NI} and the s_{SI} values. The minimum value of the PIAT will correspond to the period between when a node transmits in the last slot available within the s_{SI} and when its next transmission is in the first available slot of the next s_{SI}. Taking this into account, by means of the following equation, the minimum PIAT for each configuration can be calculated in advance (5.7).

$$PIAT_{min} = \left(s_{NI} - \frac{s_{SI} - 1}{2}\right) - \left(\frac{s_{SI} - 1}{2}\right). \tag{5.7}$$

For example, if $R_r = 10$ and $R_{SI} = 60\%$ are considered, the values of s_{NI} and s_{SI} are 169 and 101 slots, respectively, as shown previously in Table 5.4. So, for this configuration, the obtained possible minimum PIAT is 69 slots. Although the resulted PIAT has been obtained for all the defined setups, only those for $R_r = 10$ are shown below, since the conclusions obtained in this case are applicable to the setups in which $R_r = 20$ are considered. In the same way only the results for a load of 25% and 99% are shown.

Note that for $R_r = 10$, the optimal PIAT must be less than 0.2 frames to meet $R_r = 10$ ($PIAT_{Optimal} = 1$ frame/R_r). So, if the obtained maximum PIAT is less than 0.2 frames, no frames are lost between two successful transmissions. If the obtained maximum PIAT is greater than 0.2 frames but does not exceed 0.4 frames, a maximum of one frame between two successful transmissions will be lost. If the obtained maximum PIAT is greater than 0.4 frames but does not exceed 0.6 frames, a maximum of two frames between two successful transmissions will be lost and so on.

Moreover, given that the simultaneous transmissions at close range are more harmful than transmissions further away, its significance has to be taken into account when analysing the PIAT. That is why the CDFs for the PIAT have been obtained for different ranges of interest. As stated in Section 5.2.5.4, the considered range of interest are when only the transmitters whose free-space losses are > -70 dB respect to the receiver are considered (a), when only the transmitters whose free-space losses are > -75 dB respect to the receiver are considered (b) and when only the transmitters whose free-space losses are > -80 dB respect to the receiver are considered (c).

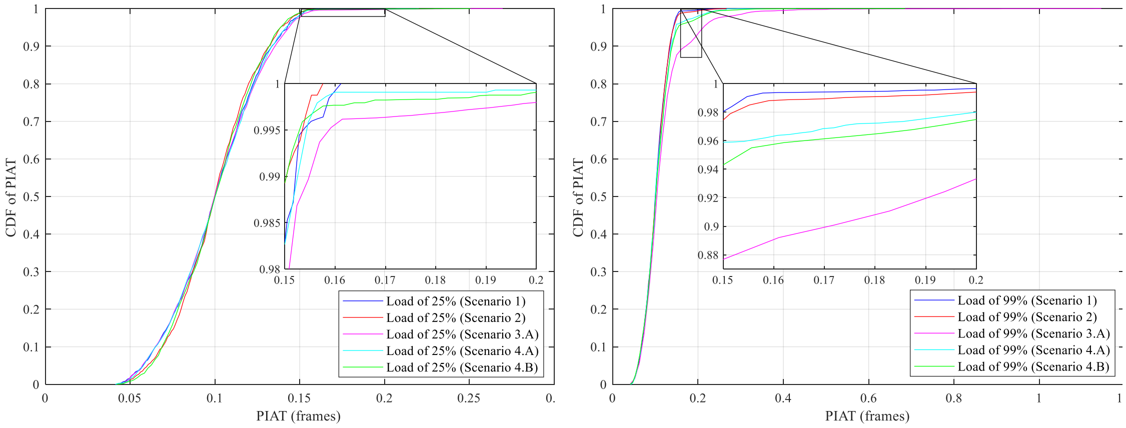
So, the CDFs for the packet inter-arrival time are shown in Figure 5.12 for a network load of 25% and 99%. Note that, the height of the step of the curves at time $n \cdot PIAT_{Optimal}$ is the probability that $(n - 1)$ consecutive packets were lost between two successful receptions.

Obtained conclusions regarding the network load

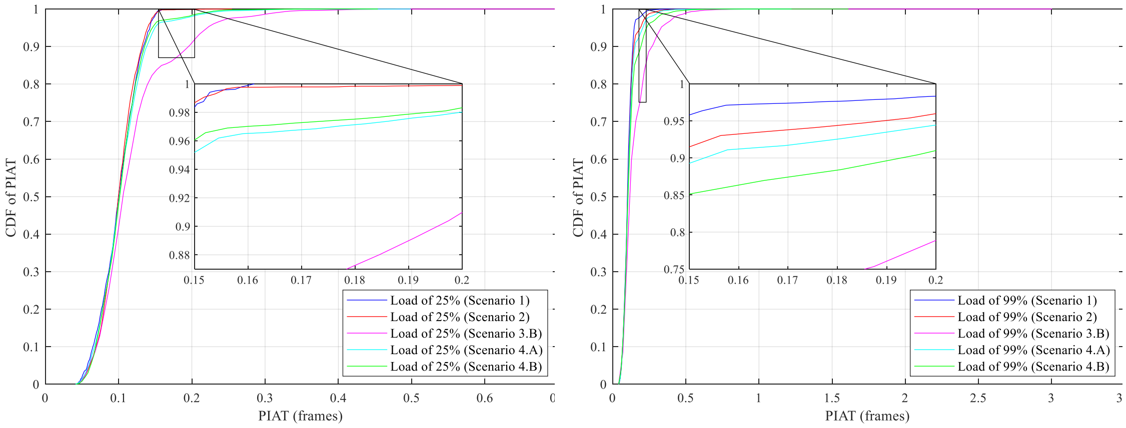
As the load of the network increases (considering the same range of interest), the obtained PIAT also increases. This effect can be seen clearly in the zoom made in the figures when no packets are lost between two successful receptions (at $PIAT_{Optimal}$). This is because given that there are more nodes that must choose a slot in which to transmit, as seen in Section 5.2.5.2, the probability that a node must reuse a slot that is assigned to a neighbouring node grows. Consequently, those packet losses due to collisions entails a greater PIAT in all the cases.

Obtained conclusions regarding the considered range of interest

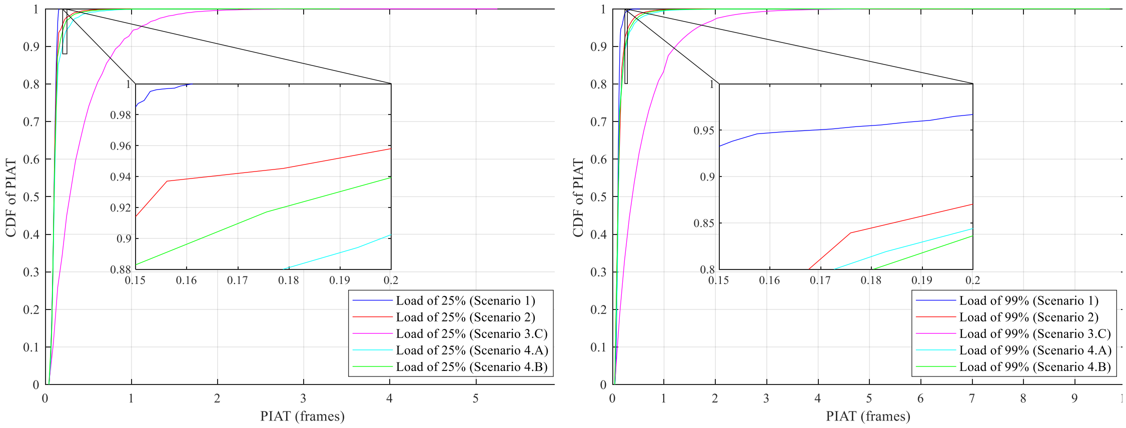
As the range of interest reduces, the obtained PIAT also reduces. When the range of interest is reduced (for example when only the transmitters whose free-space losses are > -70 dB respect to the receiver are considered (a)), all the nodes involved in the transmission/reception of the packets are close to each other. Therefore, in all cases (regardless of the load of the network or the evaluated scenario), more than 92% of consecutive packet receptions is achieved.



(a) free-space losses > -70 dB (Network load of 25%) (b) free-space losses > -70 dB (Network load of 99%)



(c) free-space losses > -75 dB (Network load of 25%) (d) free-space losses > -75 dB (Network load of 99%)



(e) free-space losses > -80 dB (Network load of 25%) (f) free-space losses > - 80 dB (Network load of 99%)

Figure 5.12: PIAT for different network load and ranges of interest.

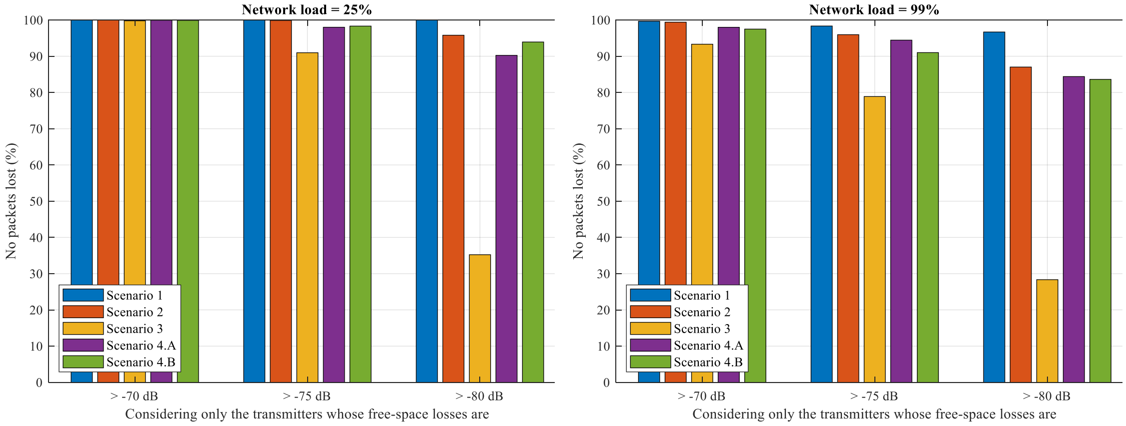
Obtained conclusions regarding the simulated scenario

As stated in Section 5.2.5.2 there are not collisions when the network load is 25% when the scenario with perfect communication conditions is taken into account (Scenario 1). This same conclusion can be reached through the obtained PIAT results since it can be seen as 100% of the packets are received before $PIAT_{Optimal}$ value regardless the considered range of interest. However, due to the way in which slot allocation is made in STDMA, in Scenario 1, when the network load is 99% a slot allocation collisions can occur as stated in Section 5.2.5.2. Therefore 99.65%, 98.34% and 96.69% of consecutive packet receptions is achieved in the considered range of interest.

In contrast, despite the progressive initialization of the nodes, when an industrial channel is considered, the probability that two or more nodes use the same slots is not zero in almost all the cases when the load is 25% as it happens in Scenario 1. Despite this, more than the 99% of consecutive packet receptions is achieved when only the transmitters whose free-space losses are > -70 dB respect to the receiver are considered and more than the 90% of consecutive packet receptions is achieved when only the transmitters whose free-space losses are > -75 dB respect to the receiver are considered. For the case in which only the transmitters whose free-space losses are > -80 dB respect to the receiver are considered, there is a huge difference between the obtained percentage of consecutive packet receptions for one scenario or another. For example, if Scenario 2 is taken into account, when the network load is 25%, 95.8% of consecutive packet receptions is achieved.

In contrast, if Scenario 3.C is taken into account, the obtained percentage is reduced to 35.23% when the network load is 25%. This is because the transmitters are always at the same relative distance respect to the receivers that correspond to a free-space loss of -80 dB. In the other scenarios, either by the random position in which the static nodes have been placed or by the movement of the nodes themselves, the channel conditions are not so harmful so the slot allocation in STDMA is made from in a more effective way avoiding potential collisions (among other things because the nodes have a better knowledge of the state of the slots).

All the obtained percentages in which no packets are lost between successful receptions (redefined as no packet lost in the figures) can be seen in a more intuitive way in Figure 5.13.



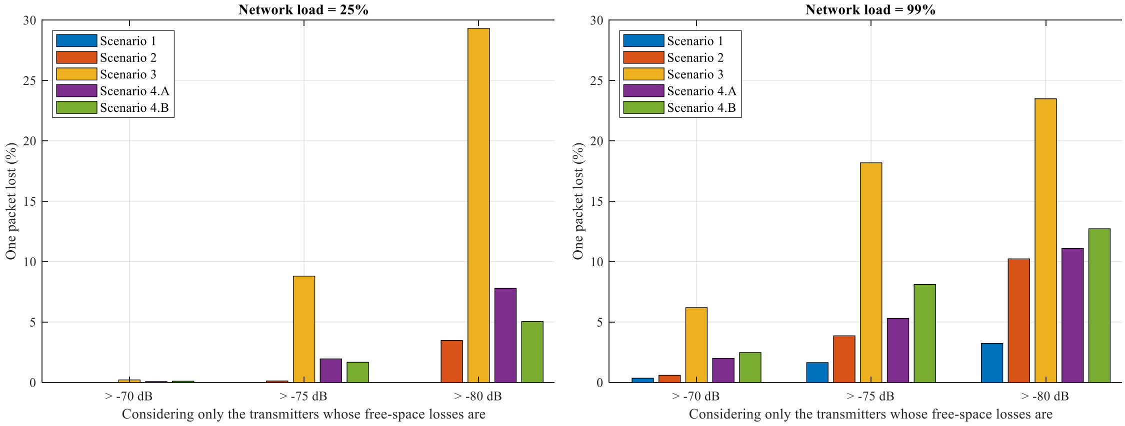
(a) network load of 25%

(b) network load of 99%

Figure 5.13: Percentage in which no packets are lost between successful receptions.

Moreover, from the CDFs curve of the PIAT besides the percentage in which no packets are lost between two successful receptions, several other results can be derived such as the percentage in which one packet is lost between two successful receptions (redefined as one packet lost in the results shown in Figure 5.14), the percentage in which more than one packets are lost between two successful receptions (redefined as more than one packet lost in the results shown in Figure 5.15) and how many packets are lost at most between two successful receptions are measured (redefined as maximum packet lost in the results shown in Figure 5.16). In all these cases, the same conclusions as those described above can be obtained.

On the one hand, both as the load of the network increases (considering the same range of interest) or as the range of interest increases, the obtained percentage in which one or more packets losses between two successful receptions as well as the maximum amount of packet losses between two successful receptions increase. On the other hand, taking into account industrial channel and Doppler shift, worsen the performance of the STDMA, being the Scenario 3.C the one with the worst performance.

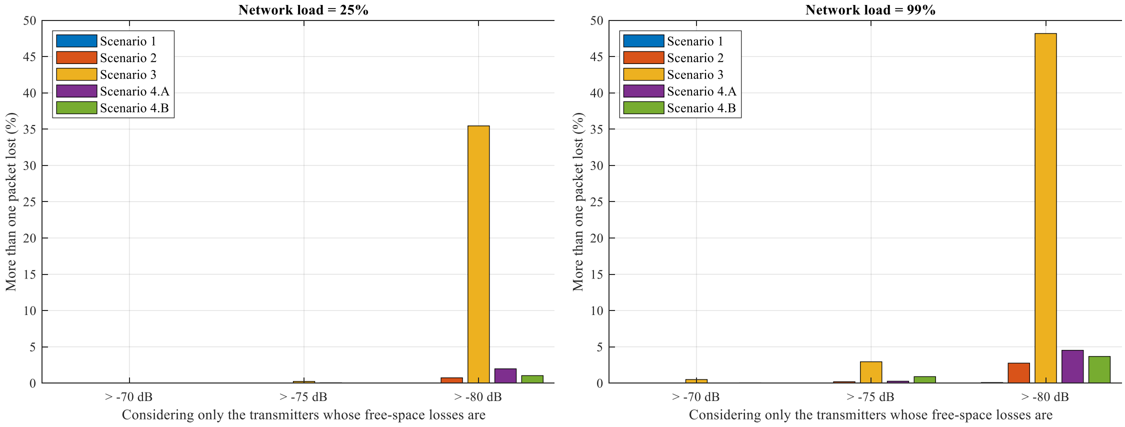


(a) network load of 25%

(b) network load of 99%

Figure 5.14: Percentage in which one packet is lost between successful receptions.

As seen in Figure 5.14, with a reduced range of interest (when free-space losses are >- 70 dB), the percentage in which one packet is lost between successful receptions is low in almost all the cases. For example, if the Scenario with the worst performance is taken into account (Scenario 3), only in the 0.21% and 6.19%, one packet is lost between successful receptions when a network load of 25% and 99% is considered. In contrast, when a high range of interest is considered (when free-space losses are >- 80 dB), in the Scenario 3 more than in the 20% one packet is lost between successful receptions.



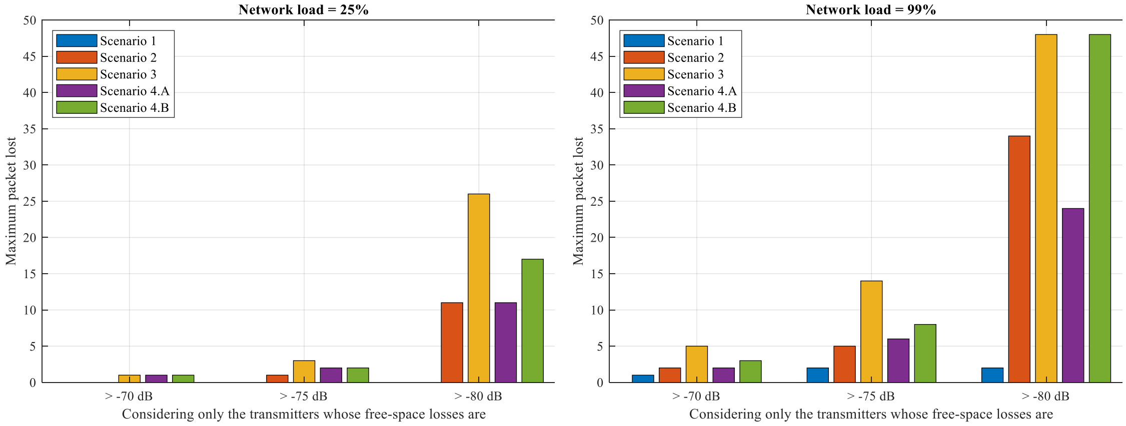
(a) network load of 25%

(b) network load of 99%

Figure 5.15: Percentage in which more than one packet is lost between successful receptions.

In contrast, as seen in Figure 5.15, regardless the considered range of interest or network load in all the cases except for the case of Scenario 3, the percentage in which more than one packet is lost between successful receptions is lower than 5%. In contraposition the Scenario 3 shows a huge percentage when considered range of interest corresponds to a free-space loss of -80 dB. In these cases, in the 35.45% and 48.18%, more than one packet is lost between successful receptions when a network load of 25% and 99% is considered respectively .

As stated previously, in the other scenarios in which industrial channels are also considered, either by the random position in which the static nodes have been placed or by the movement of the nodes themselves, the channel conditions are not so harmful, so, the nodes have a better knowledge of the state of the slots and avoid some potential collisions.



(a) network load of 25%
(b) network load of 99%

Figure 5.16: Maximum number of packets lost between successful receptions.

Finally, it can be seen in Figure 5.16, that when industrial channels are considered (Scenarios 2 to 4), there are cases in which a node does not receive any of the packets sent by a transmitter during more than a frame (the STDMA protocol is configured so that each node sends 10 packets per frame). For example, when a network load of 99% and the biggest range of interest (corresponds to a free-space losses of -80 dB) considered, a receiver node can lose from all packets sent by a node along two frames (Scenario 4.A), up to lose all packets sent by a node along more than four frames (Scenario 3 and 4.B).

5.2.7 Simulation results of the multiple STDMA network scenario

This section presents and discusses the results obtained from the simulation-based evaluation of STDMA under the multiple STDMA scenarios described in Section 5.2.2. The evaluation of the STDMA protocol has been carried out through OMNeT++ simulator in combination with VEINS [116] in order to have a mobility framework. To minimize any randomness in the results, each evaluation has been performed using several seeds.

5.2.7.1 Channel access delay

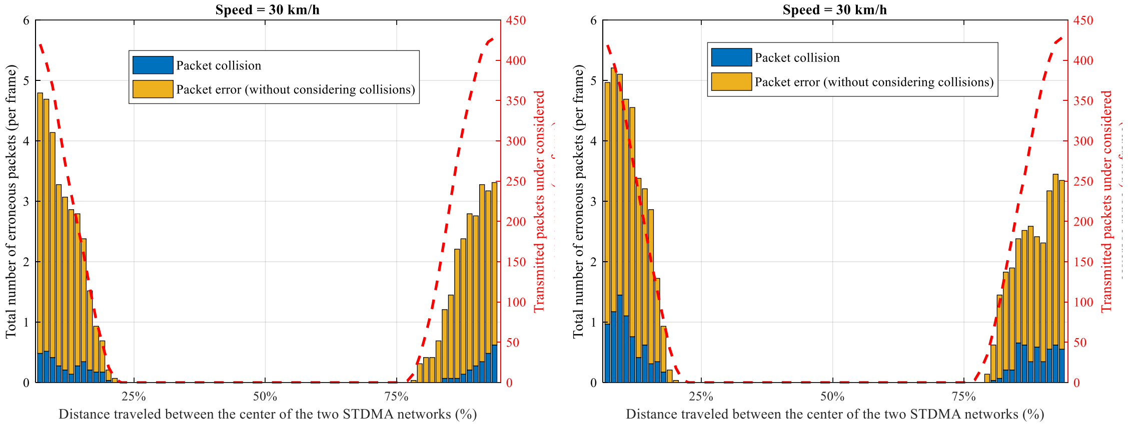
As stated in Section 5.2.6.1, the traffic generation has been scheduled so that a new packet is generated just at the start of each new s_{SI}. Therefore, the channel access delay is predictable, and its maximum will be defined by d_{SI}. So, with the simulated parameters, the maximum channel access delay is 100 slots for $R_r = 10$.

5.2.7.2 Packet losses per frame

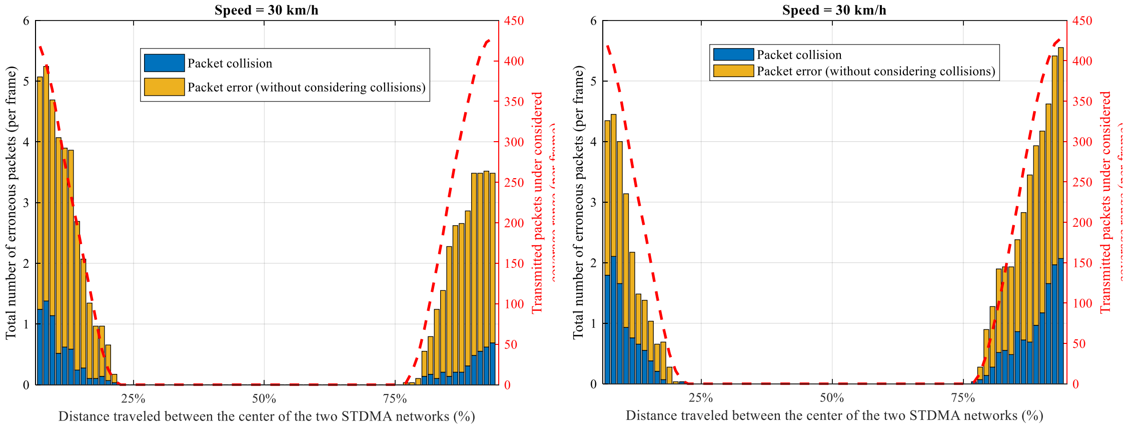
The x-axis of the following figures shows the distance travelled by the traversing node in percentage. When the traversing node is in the intermediate point of the two STDMA networks, it will have covered 50% of his route.

The y-axis on the left side of the following figures represents the total error packets (both due to collisions and due to the channel, itself). Each bar of the following figures represents an STDMA frame. In contrast, the y-axis on the right side of the following figures represents the number of transmitted packets under the considered coverage range of the traversing node, i.e. the channel load that sees the traversing node. This value is given per frame and it is represented by a dashed curve.

Figure 5.17, Figure 5.18 and Figure 5.19 show the total packet errors when a speed of 30 km/h is considered (in each figure different coverage range is considered), whereas Figure 5.20 and Figure 5.21 show the total packet errors when a speed of 3.6 km/h is considered. In contrast, Figure 5.17 and Figure 5.20 only consider transmitters whose free-space losses respect to the traversing node are >-70 dB (Setup A), Figure 5.18 and Figure 5.21 only consider transmitters whose free-space losses respect to the traversing node are >-75 dB (Setup B). Finally, although the packet losses for a speed of 30 km/h and 3.6 km/h when only transmitters whose free-space losses respect to the traversing node are >-80 dB (Setup C) are considered have been measured, only the obtained results for a speed of 30 km/h are shown below, since the conclusions obtained in this case are applicable to a speed of 3.6 km/h. Those results are shown in Figure 5.19.



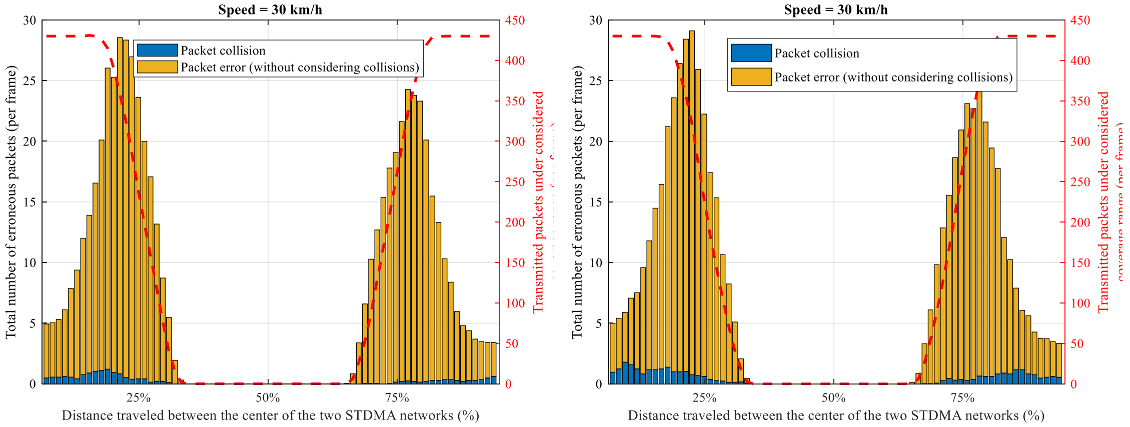
(a) Reservation timeout 3-7 frames (b) Reservation timeout 2-3 frames



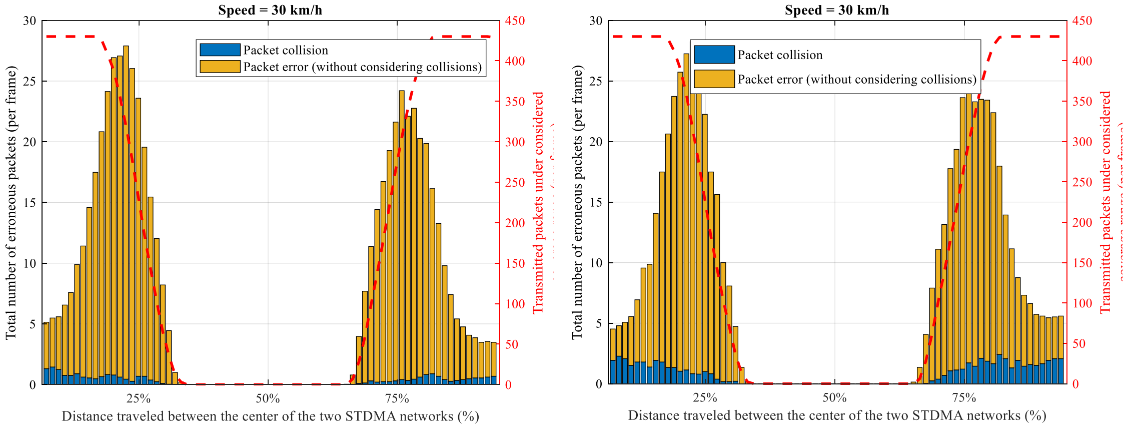
(c) Reservation timeout 2-5 frames (d) Reservation timeout 1-4 frames

Figure 5.17: Packet errors when a speed of 30 km/h is considered (Setup A).

Regardless of the simulated reservation timeout or speed, when Setup A or B is considered, and when the traversing node is located between the 25% to 75% of its route, there is no packets error because there is no transmitter under the considered coverage area. In contrast, when Setup C is considered, during all the route the traversing node is able to receive packets from one or both of the STDMA network. Moreover, in this Setup, there are a lot of packet losses especially when the traversing node moves away from the central point of the network STDMA A and when the traversing node find the network STDMA B. Also, the packet errors due to collisions are concentrated at the central point between two STDMA networks.



(a) Reservation timeout 3-7 frames (b) Reservation timeout 2-3 frames

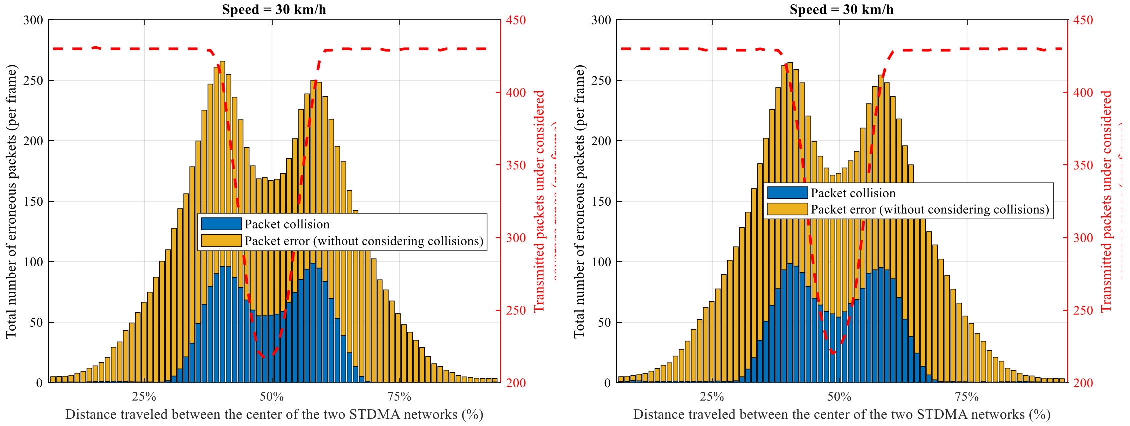


(c) Reservation timeout 2-5 frames (d) Reservation timeout 1-4 frames

Figure 5.18: Packet errors when a speed of 30 km/h is considered (Setup B).

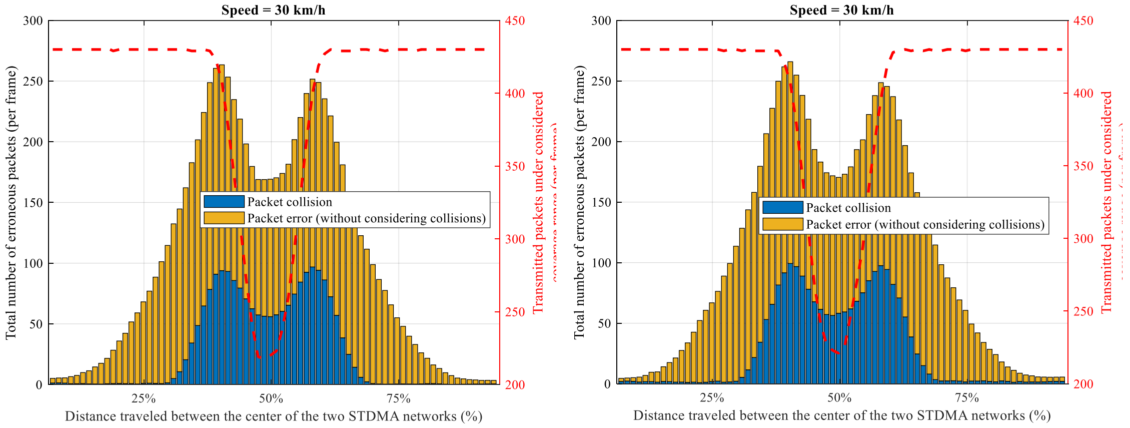
Moreover, when a reduced coverage range is considered (Setup A and B), having a reservation timeout of 3-7 frames shows better performance (the number of collisions per frame is less than in the other reservation timeout combination). In contrast, the use of a reservation timeout of 1-4 frames shows the worst performance.

Although in the case of a reservation timeout of 1-4 frames, the reallocation of the slots in made more quickly (the possible collision can be resolve before than in other reservation timeout cases), there are also more slot reallocation than in the other cases, which together with the movement of the nodes entails a greater packet collisions (new reallocation causes new collisions). In the same way, with a reservation timeout of 3-7 frames there is a 16% probability that two nodes coincide at the same instant to do the slot reallocation, with a reservation timeout of 2-5 frames or 1-4 frames this probability is 20% and finally with a reservation timeout of 2-3 frames this probability increases up to 33%.



(a) Reservation timeout 3-7 frames

(b) Reservation timeout 2-3 frames

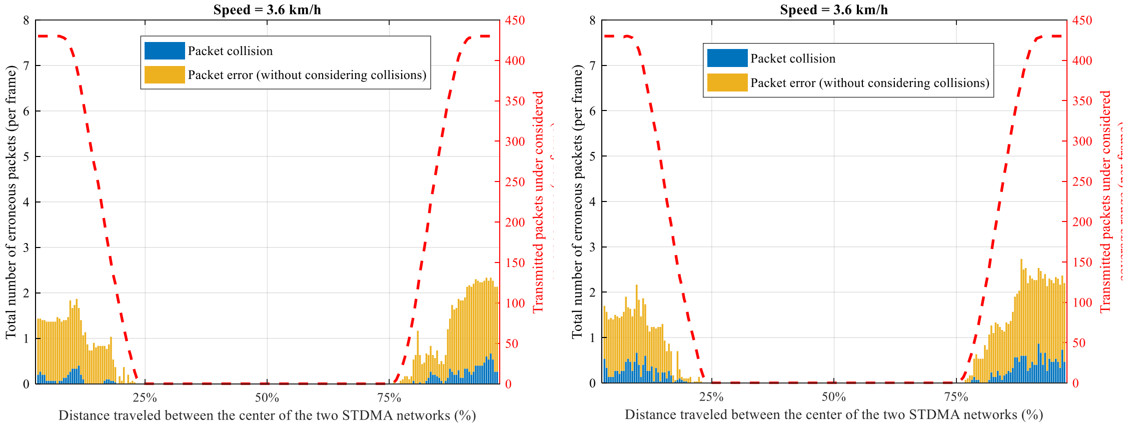


(c) Reservation timeout 2-5 frames

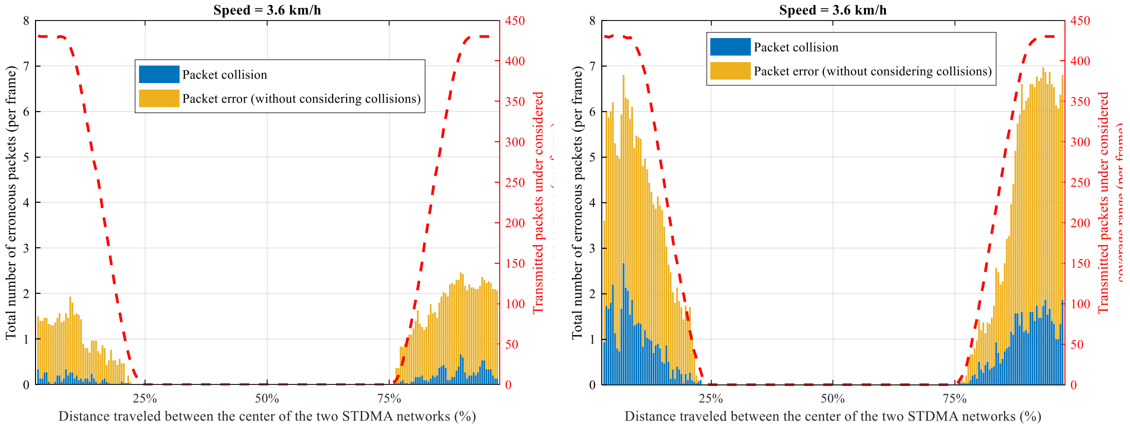
(d) Reservation timeout 1-4 frames

Figure 5.19: Packet errors when a speed of 30 km/h is considered (Setup C).

On the other hand, when a bigger coverage range is considered (Setup C), the selected timeout value has little influence on the critical points (at the centre point between the two STDMA networks). Finally, the obtained collisions per frame are lower in the case of higher speed. This is because as the traversing node moves at a higher speed, it moves away more quickly from the other transmitters nodes with which it collided.



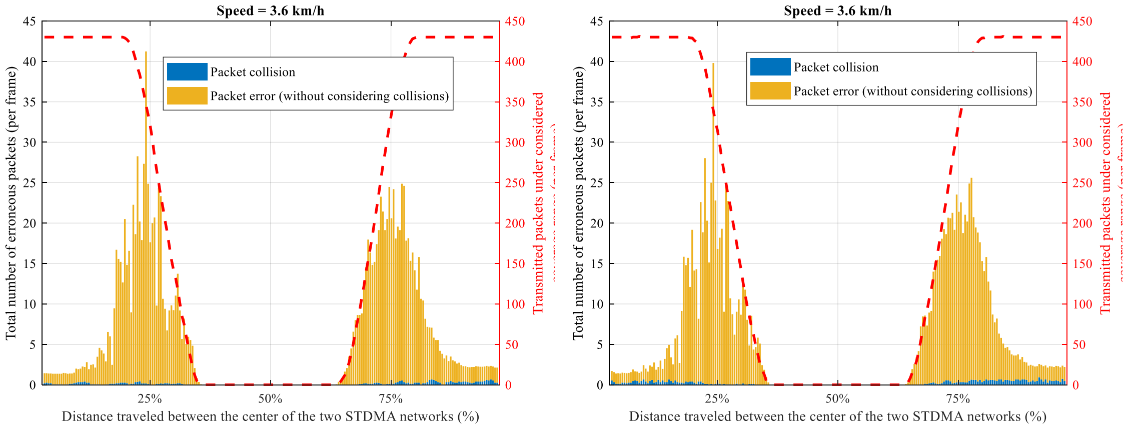
(a) Reservation timeout 3-7 frames (b) Reservation timeout 2-3 frames



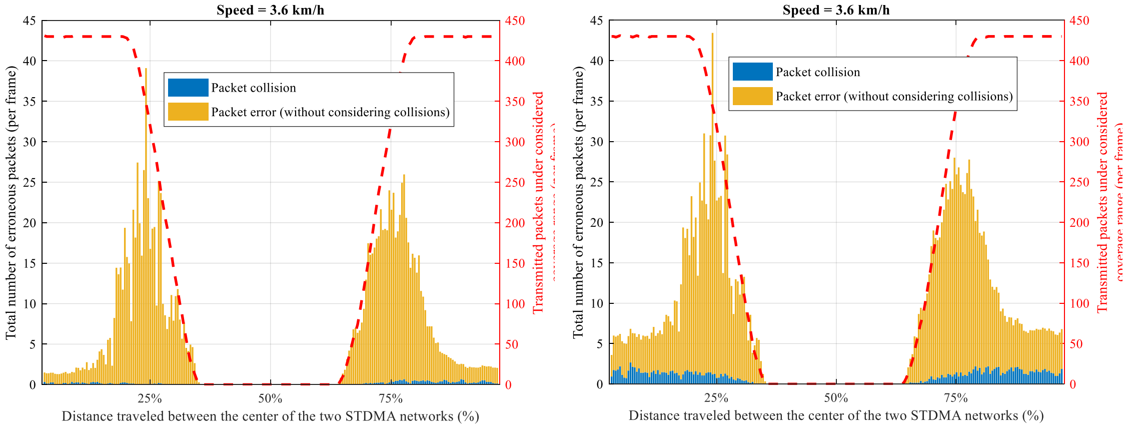
(c) Reservation timeout 2-5 frames (c) Reservation timeout 1-4 frames

Figure 5.20: Packet errors when a speed of 3.6 km/h is considered (Setup A).

In the case of packet losses due to the channel itself, it can be seen that the obtained packet losses are reduced when the considered coverage range is low (Setup A). This is because the distance between the traversing node and the transmitter nodes is reduced and in consequence, the packet error probability is reduced. In contrast, as the range of coverage considered increases, the packet errors are increased. As in the case of collisions, the packet errors due to the channel are concentrated at the central point between two STDMA networks. Moreover, as in the case of collisions, the reservation timeout of 1-4 frames shows the worst performance regardless of the speed of the nodes. This is because the collisions caused by the nodes outside the range of coverage of the traversing node are greater in this case, so that if a transmission of node within the coverage range of the traversing node is involved in a collision with a transmitter node outside the coverage range of the traversing node, the traversing node will detect this transmission as a packet error due to the channel.



(a) Reservation timeout 3-7 frames (b) Reservation timeout 2-3 frames



(c) Reservation timeout 2-5 frames (c) Reservation timeout 1-4 frames

Figure 5.21: Packet errors when a speed of 3.6 km/h is considered (Setup B).

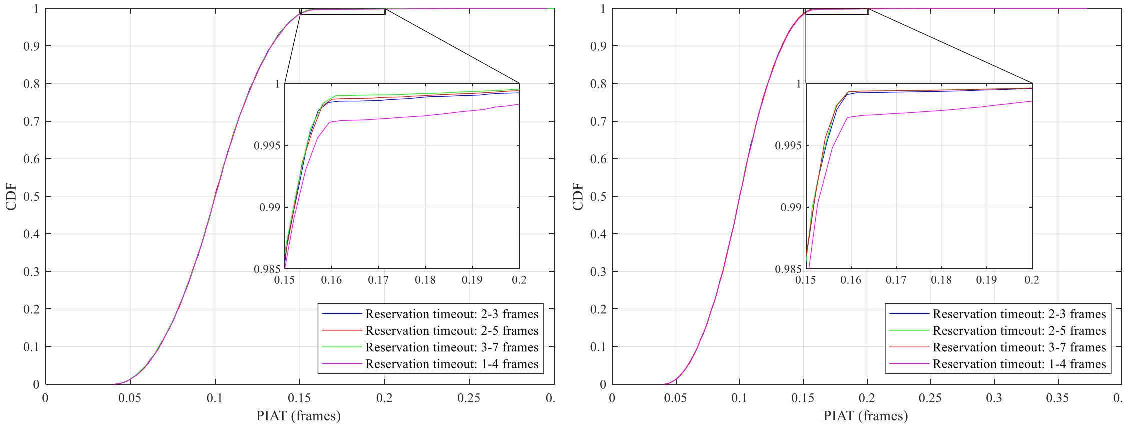
5.2.7.3 Packet Inter-Arrival Time (PIAT)

As stated in Section 5.2.6.4, if the obtained maximum PIAT is less than 0.2 frames (corresponds to $PIAT_{Optimal}$), no frames are lost between two successful transmissions.

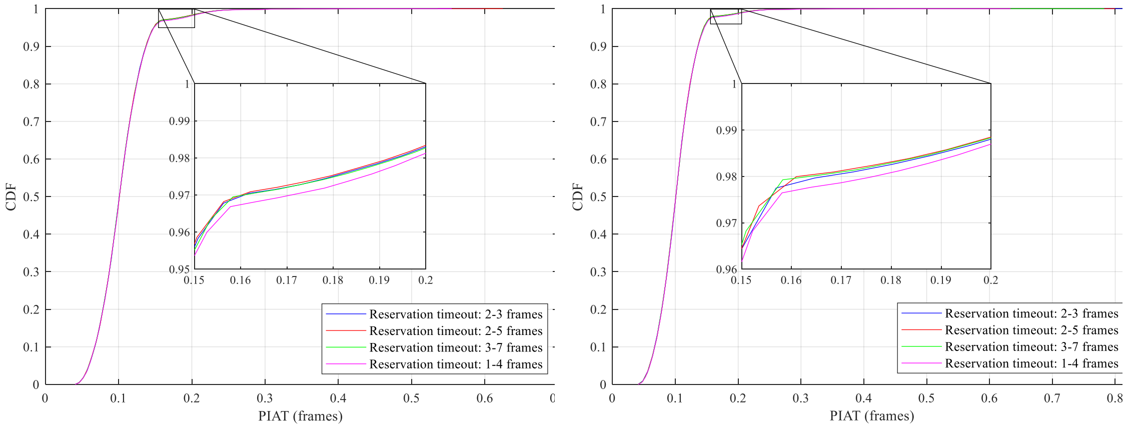
So, the CDFs for the packet inter-arrival time are shown in Figure 5.22 for a speed of 30 km/h and 3.6 km/h. It can be seen in all the cases, that as the considering coverage range increases, the PIAT increases considerably.

Moreover, the height of the step of the curves at time $n \cdot PIAT_{Optimal}$ is the probability that (n – 1) consecutive packets were lost between two successful receptions. So, when only transmitters whose free-space losses are > -70 dBm, one packet is lost at most between two successful receptions regardless of the speed of the simulated nodes. When only transmitters whose free-space losses are > -75 dBm, three (when the speed is 30 km/h) or four (when the speed is 3.6 km/h) packets are lost at most between two successful receptions. When only transmitters whose free-space losses are > -80 dBm, up to 31 packets are lost between two successful receptions (only measured when the speed is 30 km/h).

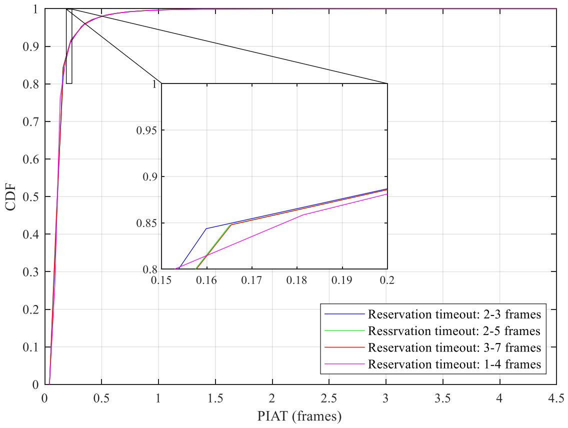
Moreover, the resulted PIAT value in all the cases is higher for a reservation timeout of 1-4 frames. As stated previously, this reservation timeout combination also shows the worst performance related to packet errors due to collisions and due to the channel, itself. In contrast, the curves obtained for the other three reservation timeout are very similar.



(a) free-space losses > -70 dB (speed of 30 km/h)   (b) free-space losses > -70 dB (speed of 3.6 km/h)



(c) free-space losses > -75 dB (speed of 30 km/h)   (d) free-space losses > -75 dB (speed of 3.6 km/h)



(e) free-space losses > -80 dB (speed of 30 km/h)

Figure 5.22: PIAT for different speeds and ranges of interest.

In addition, when considering only the transmitters whose free-space losses are > -70 dB respect to the traversing node (Setup A), more than the 99.5% of consecutive packet receptions is achieved regardless the speed of the nodes or the considered reservation timeout. When considering only the transmitters whose free-space losses are > -75 dB respect to the traversing node (Setup B), more than the 98% of consecutive packet receptions is achieved regardless the speed of the nodes or the considered reservation timeout, although having a reduced speed entails a better performance. Finally, when considering only the transmitters whose free-space losses are > -80 dB respect to the traversing node (Setup C), the 98% of consecutive packet receptions is achieved.

Finally, when considering only the transmitters whose free-space losses are > -70 dB respect to the traversing node (Setup A), the 100% of consecutive packet receptions is achieved just losing one packet between two successful receptions regardless the speed of the nodes or the considered reservation timeout. When considering only the transmitters whose free-space losses are > -75 dB respect to the traversing node (Setup B), the 99% of consecutive packet receptions is achieved just losing one packet between two successful receptions regardless the speed of the nodes or the considered reservation timeout. Finally, when considering only the transmitters whose free-space losses are > -80 dB respect to the traversing node (Setup C), the 96% of consecutive packet receptions is achieved just losing one packet between two successful receptions regardless the speed of the nodes or the considered reservation timeout

5.3 General conclusions

By selecting the proper combination of STDMA configuration parameters, the STDMA protocol can meet the end-to-end delay and jitter requirements needed in FA applications. For that, the value of R_r together with the duration of the frame must be increased and the value of s_{SI} decreased. Nevertheless, a reduced s_{SI} implies a greater collision probability between simultaneous transmissions.

In contrast, when industrial channels are taken into account, the required PLR, which may range from 10^{-6} to 10^{-12} in FA applications, cannot be met as shown in the obtained results especially when considering a broad coverage range. Although through STDMA it is possible that the transmissions of two or more nodes collide, the packet losses are mostly due to the channel. The offset parameter included in the STDMA packets helps to avoid these collisions to a great extent.

Moreover, every time the report rate (R_r) is changed, a node using STDMA must enter the initialization phase and thus, a packet is dropped at the transmitter.

Finally, the temporal synchronization between the nodes must also be addressed to ensure correct coordination between the nodes in an industrial environment. In STDMA, this synchronization is done through GPS systems. This, in addition to the cost involved and the lack of GPS signal in some industrial scenarios, is an inaccurate method given the multipath caused in the hostile environments of industrial applications.

Despite all the mentioned drawbacks, the self-organization ability facilitated by STDMA remains a particularly interesting functionality for industrial applications. Thanks to this mechanism, the STDMA protocol can solve overload situations and handle a large number of simultaneous devices. Besides, by means of this mechanism, it is possible to cope with the changes in the topology dynamically offering great flexibility to the system.

5.4 Chapter summary

In this chapter, an extensive simulation-based evaluation of STDMA is done in order to analyse its viability as an alternative for carrying out a handover without centralized systems in FA applications. The analysis of STDMA protocol under a multipath dispersed time-variant industrial channel in the presence of Doppler shift is the main contribution of this chapter. The performance of the protocol has been evaluated through OMNeT++ simulations in combination with VEINS in order to have a mobility framework.

For the evaluation of the protocol, several scenarios for single and multiple STDMA networks have been considered. The considered scenarios focus on the evaluation of the performance of STDMA in industrial environments, whose requirements in terms of reliability and determinism tend to be more restrictive than in vehicular environments.

Moreover, in order to evaluate the requirements on delay, reliability, fairness and scalability, several performance metrics such as channel access delay, slot distribution occupation, packet error rate and packet inter-arrival time have been measured.

By selecting the proper combination of configuration parameters, the STDMA protocol can meet the end-to-end delay and jitter requirements needed in FA applications. However, the required Packet Loss Rate, cannot be met with STDMA protocol especially when considering a broad coverage range. Although through STDMA it is possible that the transmissions of two or more nodes collide, the packet losses are mostly due to the channel. The offset parameter included in the STDMA packets helps to avoid these collisions to a great extent.

Moreover, despite the possible collisions, it is very unlikely that the same nodes collide in their next assigned slot. Consequently, this entails a lower PIAT. Note that both the PER and the PIAT are related since the PER measures the percentage of erroneous packets and the PIAT established if the packet losses are evenly distributed or consecutive. In this way, a lower PIAT value is more desirable for the same PER.

Despite the obtained packet losses and the need of a GPS system in order to ensure a temporal synchronization between the nodes, the STDMA protocol can solve the overload situations and cope with the changes in the topology dynamically, offering great flexibility to the system.

Chapter 6

Conclusions and future work

We conclude this thesis report by stating the conclusions and the main contributions obtained from the whole research carried out during this doctoral thesis. Finally, a set of tasks that would complement and enhance the work done in this doctoral thesis are proposed.

6.1 Conclusions

This thesis evaluates the impact of mobile nodes in industrial applications with strict reliability and time constraints in both centralized and decentralized network topologies. As existing wireless technologies do not fully satisfy the stringent requirements of the most critical industrial applications, wired, centralized networks are often used. However, when the application requires mobility, there is no other way than using wireless communications. So, the adoption of wireless communications can be seen as an extension to the existing wired networks in order to create hybrid networks with mobility requirements.

The design of a proper communication solution depends mainly on the choice of the MAC protocol. Besides that, the changes in the topology due to the movement of the wireless devices must be managed correctly in order not to affect the performance of the entire network.

In the first part of this thesis a centralized hybrid MAC scheme designed for industrial applications with strict requirements in terms of robustness, determinism and RT is proposed and evaluated. Network Calculus and OMNeT have been used to determine the performance of the proposed hybrid architecture. With the proposed hybrid MAC scheme, the APs are the responsible of calculating and distributing the scheduler that will follow the nodes under its coverage area. This scheduler includes the transmissions instant of every RT data packets and ACKs. Hence, provided results show that the transmission of periodic RT critical traffic is not affected by the transmission of non-critical one with the proposed superframe structure. The first ones will be transmitted during the communication period dedicated to transmit/receive the pre-defined periodic RT data packets. In contrast, the non-critical one will be transmitter during the communication period dedicated to transmitting the BE information using the legacy IEEE 802.11 MAC. Moreover, results show that the transmissions and retransmissions are adapted to tight control cycles.

Furthermore, in order to incorporate mobile devices to the proposed centralized hybrid architecture, a soft-handover algorithm is proposed that does not require a second radio interface the network overhead. The performance of the proposed soft-handover algorithm is compared through OMNeT simulations with other handover algorithms recently proposed in the literature. The results show that the proposed soft-handover algorithm guarantees a seamless communication during the handover process without interrupting the communication.

In the last part of this thesis, distributed or ad-hoc networks are analysed in order to assess the impact of the wireless nodes in those network topologies. Specifically, the STDMA protocol is evaluated to analyse its viability as an alternative to executing a handover without centralized systems in industrial applications. The analysis has been carried out through OMNeT simulations under a multipath dispersed time-variant industrial channel subject to a Doppler shift. The results show that, although through STDMA it is possible that the transmissions of two or more nodes collide, the packet losses are mostly due to the channel. Furthermore, the channel access delay is predictable through STDMA, unlike other decentralized protocols. Finally, the results show that this protocol can solve overload situations and can handle a large number of simultaneous devices.

6.2 Thesis Contributions

The main contributions of this research work are the following:

- A hybrid centralized architecture is proposed, specifically designed for scenarios with strict requirements in terms of robustness, determinism and RT.

- In order to incorporate mobile devices to the proposed hybrid architecture, a soft-handover algorithm is designed and validated, which guarantees an uninterrupted communication during its execution without the need for a second radio interface and with a reduced growth in network overhead.

- The STDMA protocol is analysed as an alternative for carrying out a handover without centralized systems in industrial applications.

6.3 Suggestions for Further Research

Many issues described in this PhD dissertation can be addressed in the future as improvements and extensions of the current work. These are some of the suggestions for further research:

- To contemplate other metrics such as PER or channel statistics along with the RSSI when the handover decision is taken in order to improve the soft-handover algorithm performance.

- To integrate the proposed soft-handover algorithm into future versions of SHARP [117], [118], a novel hybrid network specially designed to guarantee the 1 ms control cycle required by most critical industrial applications.

- To propose a time synchronization algorithm for distributed architectures to use it as a backup system when there is no GPS signal or to use it as the main synchronization algorithm in a decentralized network topology.

- To include a rate adaptation algorithm for the centralized and decentralized MAC schemes considered to determine the optimal data transmission rate according to the conditions of the wireless channel.

- To extend the study of the RT performance of the proposed hybrid centralized architecture and the STDMA protocol to event-triggered traffic related to safety-critical messages.

- To build a real-world testbed in order to perform experimental validations.

- To investigate other decentralized communication technologies, such as cellular networks, in order to compare its performance with the STDMA protocol.

Appendix A
Publications

The following papers have been published or are under preparation for publication in refereed journal and conference proceedings. Those marked by † correspond to a contribution included in this thesis.

Journal Paper:

- Z. Fernández, Ó. Seijo, M. Mendicute and I. Val, "Analysis and Evaluation of a Hybrid Architecture for Distributed Control Systems with Mobility Requirements", under preparation for its submission to IEEE Access Journal. †
- Z. Fernández, M. Mendicute, E. Uhlemann, A. Balador and I. Val, "Interference Analysis of STDMA When Used in Industrial Scenarios", under preparation for its submission to IEEE Access Journal. †

International conference papers:

- Z. Fernández, P. M. Rodríguez, M. Mendicute and I.Val, "An improved wireless MAC protocol for priority based data delivery", in 21st IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Berlin, Germany, September 2016.
- Z. Fernández, C. Cruces, M. Mendicute and I. Val, "Deterministic real-time access point concepts for industrial hybrid Ethernet/IEEE 802.11 networks", in 13th IEEE International Workshop of Electronics, Control, Measurement, Signals and their application to Mechatronics (ECMSM), Donostia-San Sebastian, Spain, May 2017. †
- Z. Fernández, C. Cruces, M. Mendicute and I. Val, "Deterministic MAC Access Control Scheme for Industrial Hybrid IEEE 802.3/IEEE 802.11 Networks", in 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Limassol, Cyprus, September 2017. †
- Ó. Seijo, Z. Fernández, I. Val and J. A. López-Fernández, "SHARP: A Novel Hybrid Architecture for Industrial Wireless Sensor and Actuator Networks", 14th IEEE International Workshop on Factory Communication Systems (WFCS), Imperia, Italy, June 2018.
- Z. Fernández, Ó. Seijo, M. Mendicute and I. Val, "Soft-Handover Algorithm for Hybrid Industrial Wireless Sensor and Actuator Networks", in 23rd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Torino, Italy, September 2018. †
- Ó. Seijo, Z. Fernández, I. Val and J. A. López-Fernández, "SHARP: Towards the Integration of Time-Sensitive Communications in Legacy LAN/WLAN", IEEE

Global Communications Conference (Globecom Workshops), Abu Dhabi, United Arab Emirates, December 2018.

- Z. Fernández, M. Mendicute, E. Uhlemann and I. Val, “Analysis and Evaluation of Self-Organizing TDMA for Industrial Applications”, in 15th IEEE International Workshop on Factory Communication Systems (WFCS), Sundsvall, Sweden, May 2019. †

References

[1] Z. Ma, M. Xiao, Y. Xiao, Z. Pang, H. V. Poor, and B. Vucetic, "High-reliability and Low-latency Wireless Communication for Internet of Things: Challenges, Fundamentals and Enabling Technologies," *IEEE Internet Things J.*, pp. 1–25, 2019.

[2] M. Luvisotto, Z. Pang, and D. Dzung, "High-Performance Wireless Networks for Industrial Control Applications: New Targets and Feasibility," *Proc. IEEE*, pp. 1–20, 2019.

[3] Z. Fernandez, C. Cruces, I. Val, and M. Mendicute, "Deterministic real-time access point concepts for industrial hybrid Ethernet/IEEE 802.11 networks," in *IEEE International Workshop of Electronics, Control, Measurement, Signals and their application to Mechatronics (ECMSM)*, 2017.

[4] Z. Fernandez, C. Cruces, I. Val, and M. Mendicute, "Deterministic MAC access control scheme for industrial hybrid IEEE 802.3/IEEE 802.11 networks," in *IEEE Conference on Emerging Technologies and Factory Automation (ETFA)*, 2017, pp. 1–8.

[5] Z. Fernández, Ó. Seijo, I. Val, and M. Mendicute, "Soft-handover algorithm for hybrid industrial wireless sensor and actuator networks," in *IEEE Conference on Emerging Technologies and Factory Automation (ETFA)*, 2018, pp. 1–8.

[6] Z. Fernández, I. Val, M. Mendicute, and E. Uhlemann, "Analysis and Evaluation of Self-Organizing TDMA for Industrial Applications," in *IEEE Workshop on Factory Communication Systems (WFCS)*, 2019, p. 8.

[7] A. Frotzscher *et al.*, "Requirements and current solutions of wireless communication in industrial automation," in *IEEE International Conference on Communications (ICC)*, 2014, pp. 67–72.

[8] M. C. Lucas-Estañ, M. Sepulcre, T. P. Raptis, A. Passarella, and M. Conti, "Emerging Trends in Hybrid Wireless Communication and Data Management for the Industry 4.0," *Electronics*, vol. 7, no. 12, p. 19, 2018.

[9] S. Dietrich, G. May, O. Wetter, H. Heeren, and G. Fohler, "Performance Indicators and Use Case Analysis for Wireless Networks in Factory Automation," in *IEEE Conference on Emerging Technologies and Factory Automation (ETFA)*, 2017.

[10] P. Schulz *et al.*, "Latency critical IoT applications in 5G: perspective on the design of radio interface and network architecture," *IEEE Commun. Mag.*, vol. 55, no. 2, pp. 70–78, 2017.

[11] A. Araujo *et al.*, "Wireless measurement system for structural health monitoring with high time-synchronization accuracy," *IEEE Trans. Instrum. Meas.*, vol. 61, no. 3, pp. 801–810, 2012.

[12] P. M. Rodriguez, "Spectrum Handoff Strategy for Cognitive Radio-based MAC for Time-Critical and Mission-Critical Industrial Wireless Sensor and Actuator Networks (Tesis)," 2016.

[13] Z. Fernandez, P. M. Rodriguez, I. Val, and M. Mendicute, "An improved wireless MAC protocol for priority based data delivery," in *IEEE International Conference on Emerging*

Technologies and Factory Automation, *ETFA*, 2016, vol. 2016-Novem.

[14] L. Underberg, R. Kays, S. Dietrich, and G. Fohler, “Towards hybrid wired-wireless networks in industrial applications,” in *IEEE Conference on Industrial Cyber-Physical Systems (ICPS)*, 2018, pp. 768–773.

[15] P. Gaj, J. Jasperneite, and M. Felser, “Computer Communication within Industrial Distributed Environment - a Survey,” *IEEE Trans. Ind. Informatics*, vol. 9, no. 1, pp. 182–189, 2013.

[16] T. Sauter, “The three generations of field-level networks—Evolution and compatibility issues,” *IEEE Trans. Ind. Electron.*, vol. 57, no. 11, pp. 3585–3595, 2010.

[17] R. Zurawski, *Industrial communication technology handbook*. 2014.

[18] W. Steiner, G. Bauer, B. Hall, and M. Paulitsch, “TTEthernet: Time-Triggered Ethernet,” *Time-Triggered Commun.*, pp. 181–221, 2011.

[19] “Time-Sensitive Networking Task Group.” [Online]. Available: http://ieee802.org/1/pages/tsn.html.

[20] TTTech, “IEEE TSN (Time-Sensitive Networking): A Deterministic Ethernet Standard,” pp. 1–9, 2015.

[21] “The Deterministic Ethernet Guide.” [Online]. Available: http://www.deterministicethernet.com/#!time-sensitive-networking--tsn-.

[22] A. A. Kumar S., K. Øvsthus, and L. M. Kristensen, “An industrial perspective on wireless sensor networks — A survey of requirements, protocols, and challenges,” *IEEE Commun. Surv. Tutorials*, vol. 16, no. 3, pp. 1391–1412, 2014.

[23] “IEEE Std 802.15.4^{TM}-2015 for Low-Rate Wireless Personal Area Networks (WPANs),” p. 709, 2015.

[24] *ZigBee specification*. ZigBee Alliance, 2012.

[25] “HART Field Communication Protocol Specification, Revision 7.0, HART Communication Foundation Std.,” 2007. [Online]. Available: https://fieldcommgroup.org/technologies/hart.

[26] “ISA-100.11a Wireless Systems for Industrial Automation: Process Control and Related Applications, International Society of Automation (ISA) Std.,” 2009.

[27] “IEC PAS 62601: Industrial networks - Wireless communication network and communication profiles - WIA-PA, International Electrotechnical Commission (IEC) Std.,” 2015.

[28] G. Zhao, M. A. Imran, Z. Pang, Z. Chen, and L. Li, “Toward Real-Time Control in Future Wireless Networks: Communication-Control Co-Design,” *IEEE Commun. Mag.*, vol. 57, no. 2, pp. 138–144, 2019.

[29] W. Shen, T. Zhang, F. Barac, and M. Gidlund, “PriorityMAC: A priority-enhanced MAC protocol for critical traffic in industrial wireless sensor and actuator networks,” *IEEE Trans. Ind. Informatics*, pp. 824–835, 2014.

[30] P. Suriyachai, U. Roedig, and A. Scott, “A survey of MAC protocols for mission-critical

applications in wireless sensor networks," *IEEE Commun. Surv. Tutorials*, vol. 14, no. 2, pp. 240–264, 2012.

[31] T. Zhong, C. Mengjin, Z. Peng, and W. Hong, "Real-time communication in WIA-PA industrial wireless networks," in *IEEE International Conference on Computer Science and Information Technology (ICCSIT),* 2010, pp. 600–605.

[32] G. Scheible, D. Dzung, J. Endresen, and J. E. Frey, "Unplugged but connected - Design and implementation of a truly wireless real-time sensor/actuator interface," *IEEE Ind. Electron. Mag.*, vol. 1, no. 2, pp. 25–34, 2007.

[33] J. Kjellsson, A. E. Vallestad, R. Steigmann, and D. Dzung, "Integration of a wireless I/O interface for PROFIBUS and PROFINET for factory automation," *IEEE Trans. Ind. Electron.*, vol. 56, no. 10, pp. 4279–4287, 2009.

[34] V. C. Gungor and G. P. Hancke, "Industrial Wireless Sensor Networks: Challenges, Design Principles, and Technical Approaches," *IEEE Trans. Ind. Electron.*, vol. 56, pp. 4258–4265, 2009.

[35] M. Luvisotto, Z. Pang, D. Dzung, M. Zhan, and X. Jiang, "Physical Layer Design of High Performance Wireless Transmission for Critical Control Applications," *IEEE Trans. Ind. Informatics*, pp. 1551–3203, 2017.

[36] I. E. C. (IEC) Std., "IEC PAS 62948: Industrial networkswireless communication network and communication profiles–WIA-F," 2015.

[37] S. AG, "http://w3.siemens.com/mcms/industrial-communication/en/industrial-wireless-communication/network_components/Pages/network-components-iwlan.aspx." .

[38] E. Toscano, F. Misenti, and L. Lo Bello, "A traffic scheduler for real-time wireless communication in adaptable industrial automation systems," in *IEEE Conference on Emerging Technologies and Factory Automation (ETFA)*, 2010.

[39] P. Suriyachai, J. Brown, and U. Roedig, "Time-Critical Data Delivery in Wireless Sensor Networks," in *IEEE Conference on Distributed Computing in Sensor Systems (DCOSS)*, 2010, vol. 5516, pp. 145–158.

[40] M. Atto and C. Guy, "Wireless Sensor Networks : MAC Protocols and Real Time Applications," in *Annual Post Graduate Symposium on the Convergence of Telecommunications, Networking and Broadcasting*, 2012, pp. 1–6.

[41] L. H. A. Correia, T.-D. Tran, V. N. S. S. Pereira, J. C. Giacomin, and J. M. Sá Silva, "DynMAC: A resistant MAC protocol to coexistence in wireless sensor networks," *Comput. Networks*, vol. 76, pp. 1–16, 2015.

[42] L. Ma, H. Leung, and D. Li, "Hybrid TDMA/CDMA MAC Protocol for Wireless Sensor Networks," *J. Networks*, vol. 9, no. 10, pp. 2665–2673, 2014.

[43] M. Lavassani, F. Barac, M. Gidlund, and T. Zhang, "Handling event-triggered traffic of safety and closed-loop control systems in WSANs," in *IEEE International Conference on Industrial Informatics (INDIN),* 2016, pp. 631–636.

[44] T. Zheng, M. Gidlund, and J. Åkerberg, "WirArb: A New MAC Protocol for Time Critical," *IEEE Sens. J.*, pp. 1–13, 2015.

[45] H. Farag, M. Gidlund, and P. Österberg, "A Delay-Bounded MAC Protocol for Mission-

and Time-Critical Applications in Industrial Wireless Sensor Networks,” *IEEE Sens. J.*, vol. 18, no. 6, pp. 2607–2616, 2018.

[46] “IEEE Std 802.11^{TM}-2016 - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications,” p. 3534, 2016.

[47] H. Trsek and J. Jasperneite, “An isochronous medium access for real-time wireless communications in industrial automation systems—A use case for wireless clock synchronization,” in *IEEE Symposium on Precision Clock Synchronization for Measurement Control and Communication (ISPCS)*, 2011, pp. 81–86.

[48] G. Cena, L. Seno, A. Valenzano, and C. Zunino, “On the performance of IEEE 802.11e wireless infrastructures for soft-real-time industrial applications,” *IEEE Trans. Ind. Informatics*, vol. 6, no. 3, pp. 425–437, 2010.

[49] D. Deng *et al.*, “IEEE 802.11ax: highly efficient WLANs for intelligent information infrastructure,” *IEEE Commun. Mag.*, vol. 55, no. 12, pp. 52–59, 2017.

[50] G. Cena, S. Scanzio, A. Valenzano, and C. Zunino, “An Enhanced MAC to Increase Reliability in Redundant Wi-Fi Networks,” in *IEEE Workshop on Factory Communication Systems (WFCS)*, 2014, pp. 1–10.

[51] Y. Cheng, D. Yang, and H. Zhou, “Det-WiFi : A Multi-hop TDMA MAC Implementation for Industrial Deterministic Applications Based on Commodity 802.11 Hardware,” *Wirel. Commun. Mob. Comput.*, 2017.

[52] G. Tian, S. Camtepe, and Y.-C. Tian, “A deadline-constrained 802.11 MAC Protocol with QoS differentiation for soft real-time control,” *IEEE Trans. Ind. Informatics*, vol. 12, pp. 544–554, 2016.

[53] L. Seno, G. Cena, S. Scanzio, A. Valenzano, and C. Zunino, “Enhancing communication determinism in Wi-Fi networks for soft real-time industrial applications,” *IEEE Trans. Ind. Informatics*, vol. 13, no. 2, pp. 1–10, 2017.

[54] H. Trsek, “Isochronous Wireless Network for Real-time Communication in Industrial Automation,” *PhD. Diss.*, p. 182, 2016.

[55] P. Gutiérrez Peón, E. Uhlemann, W. Steiner, and M. Björkman, “Medium access control for wireless networks with diverse time and safety real-time requirements,” in *Conference of the IEEE Industrial Electronics Society (IECON)*, 2016, pp. 4665–4670.

[56] P. G. Peón, E. Uhlemann, W. Steiner, and M. Björkman, “A Wireless MAC Method with Support for Heterogeneous Data Traffic,” in *Conference of the IEEE Industrial Electronics Society (IECON)*, 2015, p. 6.

[57] M. A. Eduardo Tovar, F. Vasques, and K. R. Gerhard Hammer, “Real-time communications over hybrid wired/wireless PROFIBUS-based networks,” in *Euromicro Conference on Real-Time Systems*, 2002, pp. 142–151.

[58] G. Cena, A. Valenzano, and S. Vitturi, “Hybrid wired/wireless networks for real-time communications,” *IEEE Ind. Electron. Mag.*, vol. 2, no. 1, pp. 8–20, 2008.

[59] L. Seno, S. Vitturi, and C. Zunino, “Analysis of Ethernet Powerlink Wireless Extensions Based on the IEEE 802.11 WLAN,” *IEEE Trans. Ind. Informatics*, vol. 5, pp. 86–98, 2009.

[60] J. von Hoyningen-Huene, A. Mueller, S. Dietrich, and G. May, “Comparison of wireless

gateway concepts for industrial real-time-communication," in *IEEE Conference on Emerging Technologies and Factory Automation (ETFA)*, 2016, pp. 1–4.

[61] M. Bauer, G. May, and V. Jain, "A wireless gateway approach enabling industrial real-time communication on the field level of factory automation," in *IEEE Conference on Emerging Technologies and Factory Automation (ETFA)*, 2014, pp. 1–8.

[62] C. Cruces, R. Torrego, A. Arriola, and I. Val, "Deterministic Hybrid Architecture with Time Sensitive Network and Wireless Capabilities," in *IEEE Conference on Emerging Technologies and Factory Automation (ETFA)*, 2018, pp. 1–4.

[63] S. Dietrich, G. May, J. von Hoyningen-Huene, A. Mueller, and G. Fohler, "Frame Conversion Schemes for Cascaded Wired/Wireless Communication Networks of Factory Automation," *Mob. Networks Appl.*, pp. 1–11, 2017.

[64] A. Mishra, M. Shin, and W. Arbaugh, "An empirical analysis of the IEEE 802.11 MAC layer handoff process," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 33, no. 2, pp. 93–102, 2003.

[65] S. Feirer and T. Sauter, "Seamless handover in industrial WLAN using IEEE 802.11k," in *IEEE Symposium on Industrial Electronics (ISIE)*, 2017, pp. 1234–1239.

[66] A. A. Tabassam, H. Trsek, S. Heiss, and J. Jasperneite, "Fast and seamless handover for secure mobile industrial applications with 802.11r," in *IEEE Conference on Local Computer Networks (LCN)*, 2009, pp. 750–757.

[67] P. Machań and J. Wozniak, "On the fast BSS transition algorithms in the IEEE 802.11r local area wireless networks," *Telecommun. Syst.*, vol. 52, no. 4, pp. 2713–2720, 2013.

[68] A. Zubow, S. Zehl, and A. Wolisz, "BIGAP— Seamless handover in high performance enterprise IEEE 802.11 networks," in *IEEE/IFIP Network Operations and Management Symposium (NOMS)*, 2016, pp. 445–453.

[69] Y. Kim, H. Choi, K. Hong, M. Joo, and J. Park, "Fast handoff by multi-beacon listening in IEEE 802.11 WLAN networks," in *Conference on Ubiquitous and Future Networks (ICUFN)*, 2017, pp. 806–808.

[70] J.-P. Jeong, Y. D. Park, and Y.-J. Suh, "An efficient channel scanning scheme with dual-interfaces for seamless handoff in IEEE 802.11 WLANs," *IEEE Commun. Lett.*, vol. 22, no. 1, pp. 169–172, 2018.

[71] E. Zeljkovic, R. Riggio, and S. Latre, "Exploiting distance information for transparent access point driven Wi-Fi handovers," in *IEEE Symposium on A World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, 2017, pp. 1–6.

[72] L. Wisniewski, H. Trsek, I. Dominguez-Jaimes, A. Nagy, R. Exel, and N. Kerö, "Location-based handover in cellular IEEE 802.11 networks for factory automation," in *IEEE Conference on Emerging Technologies and Factory Automation (ETFA)*, 2010, pp. 1–8.

[73] M. Y. Chan, S. Baroudi, J. Siu, and J. Liebeherr, "Measurement-based handover method for communication-based train control systems," in *IEEE Vehicular Technology Conference (VTC Fall)*, 2017, pp. 1–6.

[74] B. Holfeld *et al.*, "Wireless Communication for Factory Automation: An opportunity for LTE and 5G systems," *IEEE Commun. Mag.*, vol. 54, no. 6, pp. 36–43, 2016.

[75] M. Gidlund, T. Lennvall, and J. Åkerberg, “Will 5G Become Yet Another Wireless Technology for Industrial Automation?,” in *IEEE International Conference on Industrial Technology (ICIT)*, 2017, pp. 1319–1324.

[76] S. A. Ashraf, I. Aktas, E. Eriksson, K. W. Helmersson, and J. Ansari, “Ultra-reliable and low-latency communication for wireless factory automation: From LTE to 5G,” in *IEEE Conference on Emerging Technologies and Factory Automation (ETFA)*, 2016.

[77] L. C. Gimenez, M. C. Cascino, M. Stefan, K. I. Pedersen, and A. F. Cattoni, “Mobility performance in slow-and high-speed LTE real scenarios,” in *IEEE Vehicular Technology Conference (VTC Spring)*, 2016, pp. 1–5.

[78] 3GPP, “Study on latency reduction techniques for LTE, TR 36.881 V14.0.0.” pp. 1–99, 2016.

[79] ITU, *Requirements related to technical performance for IMT-Advanced radio interfaces*. 2008.

[80] M. Lauridsen, L. C. Giménez, I. Rodriguez, T. B. Sørensen, and P. Mogensen, “From LTE to 5G for Connected Mobility,” *IEEE Commun. Mag.*, vol. 55, no. 3, pp. 156–162, 2017.

[81] L. Leonardi, F. Battaglia, G. Patti, and L. Lo Bello, “Industrial LoRa: a Novel Medium Access Strategy for LoRa in Industry 4 .0 Applications,” *Conf. IEEE Ind. Electron. Soc.*, vol. 1, pp. 4141–4146, 2018.

[82] C. Dombrowski and J. Gross, “EchoRing : A Low-Latency , Reliable Token-Passing MAC Protocol for Wireless Industrial Networks,” in *European Wireless Conference (EW)*, 2015, p. 8.

[83] G. Patti, G. Alderisi, and L. Lo Bello, “SchedWiFi: an innovative approach to support scheduled traffic in ad-hoc industrial IEEE 802.11 networks,” in *IEEE Conference on Emerging Technologies and Factory Automation (ETFA)*, 2015, pp. 1–9.

[84] L. Oliveira, L. Almeida, and D. Mossé, “A clockless synchronisation framework for cooperating mobile robots,” in *IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS)*, 2018, pp. 305–315.

[85] L. Almeida, F. Santos, and L. Oliveira, “Management of Cyber Physical Objects in the Future Internet of Things: Methods, Architectures and Applications,” in *Structuring communications for mobile cyber-physical systems*, 2016, pp. 51–76.

[86] I. S. 1609. .-2016 (Revision of I. S. 1609.3-2010), “IEEE standard for wireless access in vehicular environments (wave) -- networking services,” 2016.

[87] M. Hadded, P. Muhlethaler, A. Laouiti, R. Zagrouba, and L. A. Saidane, “TDMA-Based MAC Protocols for Vehicular Ad Hoc Networks: A Survey, Qualitative Analysis, and Open Research Issues,” *IEEE Commun. Surv. Tutorials*, vol. 17, no. 4, pp. 2461–2492, 2015.

[88] R. Zou, Z. Liu, L. Zhang, and M. Kamil, “A near collision free reservation based MAC protocol for VANETs,” in *IEEE Wireless Communications and Networking Conference (WCNC)*, 2014, pp. 1538–1543.

[89] ITU, “Technical characteristics for an automatic identification system using time division multiple access in the VHF maritime mobile frequency band, Techincal Repport ITU-R M.1371-5,” 2014.

[90] M. Hadded, A. Laouiti, and L. A. Zagrouba, Rachid Muhlethaler, Paul Saidane, “A fully distributed TDMA based MAC protocol for vehicular ad hoc networks,” in *International Conference on Performance Evalutaion and Modeling in Wired and Wireless networks (PEMWN)*, 2015.

[91] A. Aqsa, L. Almeida, and J. Ferreira, “A Proposal for an Improved Distributed MAC Protocol for Vehicular Networks,” in *International Conference on Future Intelligent Vehicular Technologies*, 2016, pp. 24–33.

[92] A. Aslam, L. Almeida, and F. Santos, “Using RA-TDMA to support concurrent collaborative applications in VANETs,” in *IEEE International Conference on Smart Technologies (EUROCON)*, 2017, pp. 896–901.

[93] A. Balador, A. Bohm, C. T. Calafate, and J. C. Cano, “A reliable token-based MAC protocol for V2V communication in urban VANET,” in *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, 2016, pp. 1–6.

[94] A. Balador, E. Uhlemann, C. T. Calafate, and J. C. Cano, “Supporting beacon and event-driven messages in vehicular platoons through token-based strategies,” *Sensors*, vol. 18, no. 4, pp. 1–17, 2018.

[95] 3GPP TS 36.300, ““Evolved Universal Terrestrial Radio Access (E- UTRA) and Evolved Universal Terrestrial Radio Access Network (E- UTRAN); Overall description; Stage 2,” *Rel-14 V14.0.0*, p. 2016.

[96] M. Raza, N. Aslam, H. Le-Minh, S. Hussain, Y. Cao, and N. M. Khan, “A critical analysis of research potential, challenges and future directives in industrial wireless sensor networks,” *IEEE Commun. Surv. Tutorials*, vol. 20, no. 1, pp. 39–95, 2018.

[97] W. Steiner *et al.*, “Next generation real-time networks based on IT technologies,” in *IEEE Conference on Emerging Technologies and Factory Automation (ETFA)*, 2016.

[98] *IEEE standard for local and metropolitan area networks— Bridges and bridged networks— Amendment 25: Enhancements for scheduled traffic*. 2015.

[99] J.-Y. Le Boudec and P. Thiran, *Network calculus: a theory of deterministic queuing systems for the Internet*. 2012.

[100] D. D. Khanh and A. Mifdaoui, “Timing analysis of TDMA-based networks using network calculus and integer linear programming,” in *IEEE International Symposium on Modeling, Analysis, and Simulation of Computer and Telecommunications Systems (MASCOTS)*, 2014, pp. 21–30.

[101] D.-K. Dang, A. Mifdaoui, and T. Gayraud, “Design and analysis of UWB-based network for reliable and timely communications in safety-critical avionics,” in *IEEE Workshop on Factory Communication Systems (WFCS)*, 2014, pp. 1–10.

[102] T. Strohmer and S. Beaver, “Optimal OFDM design for time-frequency dispersive channels,” *IEEE Trans. Commun.*, vol. 51, no. 7, pp. 1111–1122, 2003.

[103] F. Tramarin, S. Vitturi, M. Luvisotto, and A. Zanella, “On the use of IEEE 802.11n for industrial communications,” *IEEE Trans. Ind. Informatics*, vol. 12, pp. 1877–1886, 2016.

[104] “AD9361 Reference Manual UG-570,” *http://www.farnell.com/datasheets/2007082.pdf*.

[105] R. Croonenbroeck, L. Underberg, A. Wulf, and R. Kays, “Measurements for the

development of an enhanced model for wireless channels in industrial environments," in *IEEE Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, 2017, pp. 1–8.

[106] ETSI, "Intelligent Transport Systems (ITS); Performance Evaluation of Self-Organizing TDMA as Medium Access Control Method Applied to ITS; access layer part. ETSI TR 102 862," 2011.

[107] ETSI, "Intelligent Transport Systems (ITS); STDMA recommended parameters and settings for cooperative ITS; access layer part. ETSI TR 102 861," 2012.

[108] K. Bilstrup, E. Uhlemann, E. G. Ström, and U. Bilstrup, "On the ability of the 802.11p MAC method and STDMA to support real-time vehicle-to-vehicle communication," *EURASIP J. Wirel. Commun. Netw.*, 2009.

[109] K. Sjöberg, E. Uhlemann, and E. G. Ström, "How Severe is the Hidden Terminal Problem in VANETs when Using CSMA and STDMA?," in *IEEE Vehicular Technology Conference (VTC Fall)*, 2011.

[110] A. Alonso, D. Smely, and C. F. Mecklenbräuker, "Throughput of Self-Organizing Time Division Multiple Access MAC Layer for Vehicular Networks based on measured SNR time-series," in *IEEE Vehicular Technology Conference (VTC Fall)*, 2011, pp. 1–5.

[111] A. Alonso and C. F. Mecklenbräuker, "Stabilization time comparison of CSMA and self-organizing TDMA for different channel loads in VANETS," *Int. Conf. ITS Telecommun.*, pp. 300–305, 2012.

[112] T. Gaugel, J. Mittag, H. Hartenstein, S. Papanastasiou, and E. G. Ström, "In-depth Analysis and Evaluation of Self-Organizing TDMA," in *IEEE Vehicular Networking Conference (VNC)*, 2013, pp. 79–86.

[113] T. Gaugel, J. Mittag, H. Hartenstein, and E. G. Ström, "Understanding differences in MAC performance," in *IEEE Workshop on Smart Vehicles: Connectivity Technologies and ITS Applications (WoWMoM)*, 2014, p. 6.

[114] L. Gallo and J. Harri, "Analytical study of Self Organizing TDMA for V2X communications," *IEEE Int. Conf. Commun. Work.*, pp. 2406–2411, 2015.

[115] ITU, "Technical characteristics for a universal shipborne automatic identification system using time division multiple access in the VHF maritime mobile band ITU-R M.1371-1," 2011.

[116] C. Sommer, R. German, and F. Dressler, "Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis," *IEEE Trans. Mob. Comput.*, vol. 10, no. 1, pp. 3–15, 2011.

[117] Ó. Seijo, Z. Fernández, I. Val, and J. A. López-Fernández, "SHARP: a novel hybrid architecture for industrial wireless sensor and actuator networks," in *IEEE International Workshop on Factory Communication Systems (WFCS)*, 2018, pp. 1–10.

[118] Ó. Seijo, Z. Fernández, I. Val, and J. A. López-Fernández, "SHARP: Towards the Integration of Time-Sensitive Communications in Legacy LAN/WLAN," in *IEEE Global Communications Conference (Globecom Workshops)*, 2018, p. 7.