NOMA-based 802.11g/n: PHY analysis and MAC implementation

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Autor: Eneko Iradier Gil

Director: Pablo Angueira Buceta

Departamento: Ingeniería de comunicaciones

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Abstract

Industry 4.0 can be considered as the industrial revolution of the current century. Among others, one of its main objectives is the replacement of wired communications by wireless connectivity. The idea is to overcome the main drawbacks of the current wired ecosystem: the lack of mobility, the deployment costs, cable damage and the difficulties with scalability. However, for this purpose, the nature and requirements of the industrial applications must be taken into account, in particular, the proposed communications protocols must support very low loss rates and a strong robustness against failures. This is a very challenging condition due to the nature of the industrial environments (interference with other communication systems, reflections with metallic objects ...). In addition, another characteristic of the industrial applications is the strict requirement related to the latency. On the other hand, industrial applications are not only based on high challenging services, but also exist more flexible requirement applications, such as, web browser, email, video content or complementary information. Those services are considered Best Effort (BE) services. Eventually, in some wireless applications both critical and BE services have to be offered. For those cases, Non-Orthogonal Multiplexing Access (NOMA) technology together with the IEEE 802.11g/n standard is proposed in this document as the physical layer solution. The IEEE 802.11g/n standard has been modified in order to accommodate NOMA schemes, and then, comprehensive simulations are conducted to check and analyze the behavior of the proposed system. It has been determined that through NOMA technology it is possible to obtain better results in certain cases than those achieved in a transmission cases that implements the IEEE 802.11g/n standard in TDM/FDM basis.

Keywords: Industrial Communications, NOMA, TDMA, 802.11g/n, PHY, MAC

Laburpena

Industria 4.0 mende honetako industria iraultzatzat har daiteke. Helburu nagusienetako bat, beste guztien artean, momentu honetan haridun komunikazioak, hari gabekoen arteko konektibitateaz ordezkatzea da. Oinarrizko ideia gaur eguneko haridun ekosistemek daukaten eragozpenak gainditzean datza: mugikortasun eza, hedatze kostuak, kableen kaltetzea edota eskalabilitaterako zailtasunak. Hala ere, helburu hori betetzeko, kontuan hartu behar dira aplikazio industrialen izaera eta baldintzak, esaterako, aurkeztutako komunikazio-protokoloek galera maila oso baxuak eta erroreen aurreko sendotasuna bermatu behar dute. Zalantzarik gabe, komunikazio industrialen izaera dela eta, benetako erronka batean bilakatu da baldintza hau (beste komunikazio-sistema batzuekiko interferentziak, objektu metalikoen erreflexioak …). Horretaz gain, aplikazio industrialen beste funtsezko ezaugarri bat latentzia baxukoak izan behar direla da. Ostera, aplikazio industrialak ez dira beti baldintza zorrotzetan oinarritutakoak, badira ere baldintza malguagoak dituztenak, hala nola, web arakatzailea, emaila, bideo zerbitzuak edota informazio osagarria. Zerbitzu hauek Best Effort (BE) zerbitzuak dira. Halaber, hari gabeko komunikazio-sistema batean baldintza industrial zorrotzak dituen eta BE zerbitzuak transmititu behar dituen beharra biltzen denean, Non-Orthogonal Multiplexing Access (NOMA) teknologiak erabiltzea IEEE 802.11g/n estandarraren geruza fisikoarekin batera erabiltzea proposatzen da lan honetan. Horretarako, IEEE 802.11g/n estandarra aldatu behar izan da NOMA eskemak integratzeko, eta era berean, aurkeztutako sistemaren bilakaera egiaztatzeko eta analizatzeko, kasu errealetan oinarritutako simulazioak exekutatu dira. Teknika honen bitartez, NOMA teknologiak 802.11g/n estadarrarekin batera erabiltzean zenbait kasutan TDM/FDM eskemetan oinarritutako kasuetan baino emaitza hobeak lortzen direla egiaztatu da.

Hitz gakoak: Komunikazio Industrialak, NOMA, TDMA, 802.11g/n, PHY, MAC

Resumen

La industria 4.0 puede ser considerada como la revolución industrial de este siglo. Uno de sus principales objetivos, entre otros, es la sustitución de las comunicaciones cableadas por inalámbricas. La idea es superar los principales inconvenientes que tienen los ecosistemas cableados: falta de movilidad, los costes del despliegue, el daño en los cables y las dificultades para la escalabilidad. Sin embargo, para cumplir este objetivo, es necesario tener en cuenta la naturaleza y los requisitos de las aplicaciones industriales, en particular, los protocolos de comunicaciones propuestos deben garantizar muy bajos niveles de pérdidas y una gran robustez ante fallos. Sin duda, esta es una condición retadora debido a la naturaleza de los entornos industriales (interferencias con otros sistemas de comunicación, reflexiones de objetos metálicos…). Además, otra característica de las aplicaciones industriales es el estricto requisito de latencia que tienen. En cambio, las aplicaciones industriales no están únicamente basadas en servicios de estrictos requisitos, también existen aplicaciones con requisitos más flexibles, como, por ejemplo, el navegador web, email, contenido video o información complementaria. Estos servicios están considerados como servicios Best Effort (BE). Asimismo, dándose el caso de un sistema de comunicaciones inalámbricas que compagina servicios con requisitos de aplicaciones industriales y que también incluye la capacidad de transmitir servicios BE eficientemente, en este trabajo se propone la utilización de tecnologías Non-Orthogonal Multiplexing Access (NOMA) como capa física junto con el conocido estándar IEEE 802.11g/n. De este modo, el estándar IEEE 802.11g/n ha sido modificado con el fin de introducir esquemas NOMA, y a su vez, se ha ejecutado simulaciones realistas que han verificado y analizado el comportamiento del sistema propuesto. Mediante esta técnica, se ha demostrado que utilizando tecnologías NOMA, es posible obtener mejores resultados en diversos casos mejorando los resultados obtenidos bajo arquitecturas basadas en sistemas IEEE 802.11g/n TDM/FDM.

Palabras clave: Comunicaciones Industriales, NOMA, TDMA, 802.11g/n, PHY, MAC

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Acronym List

5G: Fifth Generation

AR: Augmented Reality

AWGN: Additive White Gaussian Noise

BLER: Block Error Rate

CA: Collision Avoidance

CCA: Clear Channel Assessment

CL: Core Layer

CSMA: Carrier Sense Multiple Access

DL: Downlink

E2E: End-to-End

EL: Enhanced Layer

FA: Factory Automation

HT: High Throughput

IEEE: Institute of Electrical and Electronics Engineers

IMT: International Mobile Telecommunications

IoT: Internet of Things

ITS: Intelligent Transport Systems

IWSN: Industrial Wireless Sensor Network

LDM: Layered Division Multiplexing

LDPC: Low Density Parity Check

MAC: Medium Access Control

MBB: Mobile Broadband

MCS: Modulation and Coding Scheme

MIMO: Multiple Input Multiple Output

NOMA: Non-Orthogonal Multiplexing Access

OFDMA: Orthogonal Frequency-Division Multiple Access

OMA: Orthogonal Multiplexing Access

PA: Process Automation

PER: Packet Error Rate

PHY: Physical Layer

PLCP: Physical Layer Convergence Protocol

PLR: Packet Loss Rate

PSDU: PLCP Service Data Unit

SISO: Single Input Single Output

SNR: Signal to Noise Ratio

TDMA: Time Division Multiple Access

TSN: Time Sensitive Network

UL: Uplink

VR: Virtual Reality

WP: Work Package

WSN: Wireless Sensor Network

1. Introduction

Industrial communications are really challenging and replacing wired communications by wireless connectivity increases the challenge difficulty. These applications have tight requirements in terms of reliability and overcome them is a topic that concerns researcher all around the world. In this document, in order to achieve higher reliability for industrial communication in comparison with what actual technologies achieve, we are presenting an innovative communication system based on NOMA schemes and the IEEE 802.11g/n wireless standard. The main contribution is to introduce NOMA as a new technique for the IEEE 802.11g/n standard physical layer. During this work not only the theoretical part of the idea is presented, but also a PHY level and a MAC level validation is developed and analyzed.

First, the background of this work is presented. This work is oriented to industrial applications, and so, in the background section, an overview through the industrial communications is done. Some general requirements are presented in order to clarify which are the minimum values that need to be achieved. Taking into account those requirements, industrial applications could be classified depending on their goal. Finally, 802.11 standard family and NOMA are introduced as trendy technologies with an interesting balance of robustness and capacity.

Once the need of this project is understood, the main objective of the work and its related secondary objectives are listed and explained. In relation to those objectives, in Section 4, the achievable benefits by scoring the goal of the project are presented. These benefits are classified into technical, social and economic benefits.

After that, an interesting summary of the literature and the topics related with the project is presented in the state of art section. At the beginning, several real use cases and applicable sectors are studied within the industrial scope together with the requirements that are imposed. This is a key section, because it defines the requirements that are going to rule this proposal validation process. In order to offer a technical perspective of the literature, the two main technologies of this project are presented, 802.11 standard family and NOMA.

Since the minimum technical aspects to understand the project are shown, in the methodology section every step forwarded to achieve the goal is detailed. This section starts explaining the overall evaluating system, which is based in Matlab and OMNeT++ simulations, for PHY and MAC layer simulations, respectively. Then, the rest of the section is divided into two parts, implementation of NOMA over 802.11g and over 802.11n. As will be explained in each section, the error correction code mechanism implemented is completely different for each standard version and, so, the reliability results are different, as well. That is why, the PHY level and MAC level validation process and results analysis is done independently for each version.

In section 7, information related with the project management is presented. First, every Work Package (WP) is listed and it is detailed the tasks that have to be done and the milestones. Each of the WP has its own duration in weeks. All the tasks, milestones and WPs are gathered in a Gantt diagram, which goes from the beginning of the project, through the last project day.

After the time and responsibility distribution, the economic section appears, in which an expense summary is presented. For it, the overall expense summary is divided into different sections: internal hours, amortizations, expenses, subcontracting and indirect costs. Finally, the total expense summary is depicted.

As in any engineering project, there are a number of risks, which may affect the development and the results. Therefore, in the risk analysis section, the risks that could appear during the project are presented. Those risks are firstly identified. After identification, specific contingency plans are designed , and finally, risks are classified in terms of impact and occurrence probability within a risk matrix.

Finally, the conclusions obtained by the development of this project are summarized and future works are as well presented.

2. Background

The fourth industrial revolution is driving the next evolution of the industrial communications. The main objective is to facilitate wireless interconnection and computerization of the traditional industrial environments, and consequently, improve the resources efficiency and the integration between processes and factories [1].

Despite the increasing popularity of wireless services, the major part of the machines are wired in a majority of the current industrial venues. In fact, is not clear that the actual wireless standards could guarantee the tight requirements posed by the industrial applications.

Wireless Sensor Networks (WSN) applications can be classified in different ways. One of them is based on the performance of data transmission, both in terms of latency and robustness. Latency refers to the timing of the data reception in the receiver Parameters such as jitter or transmission delay are often used to quantify it. Regarding robustness, it refers to the amount of correct data that is received at the destination. The most common parameters to measure it are the reception rate and the lost packet rate.

In turn, it should be noted that the performance in the domain of time and robustness are interdependent with each other, since, for example, that the data arrive late to the receiver can be considered a loss of information. The classification of the applications of the WSNs based on the two parameters explained is shown in Figure 1 [2].

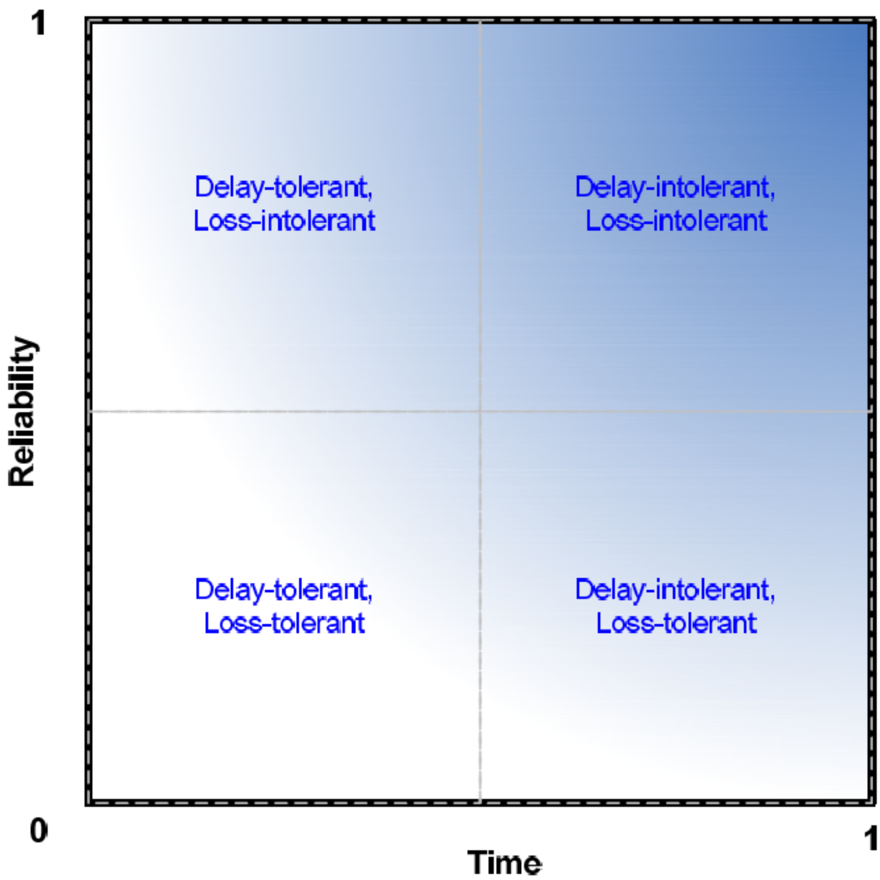


Figure 1: Application classes based on network performance [2]

In the case of industrial applications, WSNs have acquired great interest, but in order to implement them, it is necessary to guarantee compliance with their strict requirements. In the previous classification, these applications are located in the upper right quadrant, that is, they support very low loss rates and must be very robust against failures. Although these requirements are going to be presented in more detail in section 5.1, an example of the latency values and PER (Packet Error Rate) supported by the control processes are those presented in [3] through Table 1:

Control Field	Application	Latency (ms)	PER
Process Automation	Maintenance and diagnostic	> 100	$< 10^{-4}$
	Open/closed-loops	50 - 100	$< 10^{-4}$
Factory automation	Maintenance and diagnostic	> 15	$< 10^{-5}$
	Open/closed-loops	1 - 15	10^{-9} - 10^{-8}
	Stringent requirement applications	< 1	$< 10^{-9}$

Table 1: Latency and PER requirements in control processes [3]

Another classification for industrial systems is based on data delivery robustness in relation to application requirements [4]. Each system type has its own restrictions in terms of latency and robustness:

- Safety systems: Systems where immediate action on events is required in the order of seconds belong to this class e.g. fire alarm systems. The WSN nodes are deployed uniformly throughout the area of concern to cover the entire area. The nodes are usually stationary.
- Control systems
    - Closed loop regulatory systems. Control system where feedbacks are used to regulate the system. WSN nodes are deployed in the area of concern in a desired topology. Periodically and based on events, measurements are sent to the controller. Periodic measurements are critical for smooth system operation. These systems may have timing requirements that are stricter than safety systems.
    - Closed loop supervisory systems. They are similar to regulatory systems with the difference that feedbacks/measurements are not expected periodically but based on certain asynchronous events. The feedback is non-critical e.g. a supervisory system that collects statistical data and reacts only when certain trends are observed.
    - Open loop control systems. Control systems operated by a human operator, where a WSN is responsible for data collection and relaying the collected data to the central database. The operator analyzes this data and undertakes any measures if required.
- Monitoring systems
    - Alerting systems. Systems with regular/event-based alerting. An example is a WSN for continuous monitoring of temperature in a furnace and alerting at different stages, to indicate part of the work done.

- Information gathering systems. System used for data collection and data forwarding to a server. An example could be WSN nodes deployed in a field to gather data about the area of interest, such as temperature and moisture, for a specific duration of time.

Despite the fact that the term 'Industry 4.0' is currently peaking, the real situation is that most communication networks in industrial environment are wired. Specifically, they use the Ethernet standard and the TSN (Time Sensitive Network) family of standards. However, to switch to a wireless network, the first step is to implement a heterogeneous network, that is, a network composed of both a wired part and a wireless network.

So far, several technologies have emerged to implement a wireless communication network. However, none of the proposals meets all the previously explained specifications required for communications in industrial environments.

One of the options for creating a WLAN is through the implementation of the IEEE 802.11g standard, which works in the 2.4 GHz band and operates at a theoretical maximum speed of 54 Mbps [5]. The 802.11 family of standards was not designed initially for the development of industrial communications. Nevertheless, in the last few years, the use of the 802.11 standard in IWSNs (Industrial Wireless Sensor Network) has rapidly increased. One of the main advantages is of 802.11 standards is their common framework with Ethernet. This fact provides a high level of interoperability and facilitates straightforward implementation of Ethernet/WLAN internetworking functions and devices. Conversely, its medium access mechanism, CSMA/CA, does not guarantee deterministic behavior, so it is a significant challenge to ensure real-time services in a crowded spectrum [6].

However, taking into account more recent literature, there are some cross layer approach, not only from a PHY-MAC point of view, but also from the network point of view. In [7] different aspects that have to be taken into account for the design of ultra high-performance wireless networks for critical industrial control applications are detailed. In [8], SHARP (Synchronous and Hybrid Architecture for Real-time Performance) is presented, a new architecture for industrial automation. Its wireless part includes a novel PHY layer based on 802.11g integrated in a TDMA in order to guarantee determinism.

Taking into account that the IEEE 802.11g standard does not allow immediate application, this project proposes a modification of the physical layer to meet the requirements of communication services in industrial environments.

The solution proposed is the combination of current 802.11 PHY/MAC layers with a non orthogonal multiplexing technique (NOMA). This technology, as explained in section 5.3, allows several data streams to be sent simultaneously (not on a TDMA (Time Division Multiple Access) basis) and on the same channel (not a FDMA structure). The multiplexing is based on a power division structure, where each service is allocated a portion of the transmitter power. The result is a very robust upper data layer with very low error rates and a less robust lower layer that conveys larger bitrates.

3. Objectives and Scope

3.1. Main objective

The main objective of this project is to design and develop a proposal for the physical layer of the IEEE 802.11g standard based on NOMA, and its subsequent software implementation in a packet simulator that analyzes the MAC layer. It is sought that through these changes, the robustness requirements necessary to apply it in the field of industrial wireless communications are granted.

3.2. Secondary objectives

In order to achieve the main objective explained above, a set of secondary objectives are required:

1. Characterize industrial communication system requirements. This target will include a definition of functional features of industrial communication environments in order to translate them into technical requirements that must be met for a variety of applications, sectors and use cases. This objective requires an analysis of the state of the art in industrial communications. On the one hand, this goal must cover the previous studies that have been carried out and a proper identification of the research gaps. On other hand, a description of the use cases, applications and associated requirements where this project will propose contributions.
2. Characterize the physical level of both communication techniques (NOMA and IEEE 802.11g/n). This goal will include both standalone and joint evaluation of both techniques in order to design a complete system (transmission, reception and industrial channel emulation). A thorough definition of technical parameters at transmission, reception and propagation modeling is required to achieve this objective.
3. Design a validation methodology for the PHY-MAC architecture proposal. This project is based on two levels of simulation: Matlab for the PHY level and OMNeT++ for the MAC level. The project will include methodology definition, implementation in both tools and validation through extensive simulation cases. This objective requires a high level of understanding and expertise of both simulation tools.

3.3. Scope

The scope of the present project consists, on the one hand, of obtaining a Matlab prototype consisting of a transmitting part, a receiving part and an industrial channel simulator. This system allows sending two simultaneous services of different characteristics and making use of all the available bandwidth. Sending both services using 100% of the time and frequency resources simultaneously is possible using the NOMA architecture.

On the other hand, the project will analyze the performance at MAC level design in industrial environments. This goal will be based on the design and implementation of a specific software tool based on OMNeT++.

4. Benefits

Industrial communications, as discussed above, are in a transition period. This is because most of them are carried out by cable and the goal is to become wireless. Due to the demands that these communications present in industrial environments, the systems that manage to fulfill them can provide important benefits in relation to several aspects.

The benefits by the completion of this project are provided below. These are analyzed from a technical, economic and social point of view.

4.1. Technical benefits

The benefits associated with this project are related to the fact of enabling industrial wireless communications that meet a series of strict requirements to be able to use them in such an environment.

The main technical benefit is related to the advantages of wireless networks over wired networks. Wired networks usually cause problems associated with repairs and equipment substitutions as well as causing problems due to the use of cable in objects that require movement.

In addition to that, since there is currently no standardized wireless solution adapted to the industry, another benefit of the proposed approach in this project is that it allows the use of secure communications with the necessary characteristics of the area of use of them.

Finally, the proposal to use non-orthogonal multiplexing techniques increases the efficiency of spectrum use, which is a fundamental challenge today.

4.2. Economic benefits

As for the economic benefits, this proposal facilitates the transition from wired to wireless in industrial communication system. This transition implies a reduction of expenses. Specifically, the installation costs of wired communication systems are high, so moving to a wireless solution would reduce costs in that regard.

In addition, going wireless also reduces additional costs that may arise in wired systems, for instance, the isolation of equipment to avoid harmful effects, such as high temperatures. Finally, the scalability of wireless systems is less expensive, allowing a more viable adaptation of the network to the environment.

4.3. Social benefits

The social benefits are related with technical benefits. By achieving very robust communications with NOMA, the efficiency of industrial applications increases, and as a result, communications become more secure. This is a fact that benefits in particular applications related to security, such as fire alarms, as they become much more efficient.

Moreover, it should be noted that the use of wireless networks eliminates the need of human or any device presence in dangerous or difficult to access places.

Finally, the reduction of wired communication systems carries an increase in mobility. This aspect could be exploited to design more complex or useful applications, for example in robotics and factory automation fields.

5. State of Art

In this section, a study of the state of the art will be carried out, in which, first, real use cases will be studied within the industrial scope together with the requirements that are imposed. The objective of this section is to define replicable use cases that can be evaluated in this project. Secondly, the IEEE 802.11g standard will be described, giving special importance to the physical and MAC layers. Finally, the NOMA technology is presented as a proposal to achieve the previously mentioned requirements. To do this, its principles to know its operation will be described as well as the application cases where this technology is implemented today.

5.1. Real use case requirements

5.1.1. IoT applications in 5G

Besides the traditional Mobile Broadband (eMB), Internet of Things (IoT/MTMTC) and Ultra Reliable Low Latency Communications (URLLC) drive the development of 5G networks also. Therefore, in addition to the classical eMB traffic demands of high throughput and capacity, new requirements of achieving low latency and high reliability for many IoT use cases are very important. Five important use cases of latency critical IoT applications have been considered and characterized [9]:

A. Factory automation (FA): Factory automation applications are typically characterized by real-time control of machines and systems in fast production and manufacturing lines, where machine parts are in motion within a limited space. This kind of applications are usually related to URLLC communications.

B. Process automation (PA): Process automation includes applications for monitoring and diagnostics of industrial elements and processes including heating, cooling, mixing, stirring, pumping procedures, and so on. The measured values for these applications change relatively slowly.

C. Smart Grids: Smart grid applications have relatively less stringent requirements on latency and reliability compared to factory automation applications

D. Intelligent Transport Systems (ITS): Autonomous driving and the optimization of road traffic create new challenges for communications. Requirements result from different ITS use cases such as autonomous driving, road safety, and traffic efficiency services

E. Professional audio: The majority of today’s professional audio links is built based on conventional analog transmission techniques in dedicated licensed frequency bands in the VHF and UHF ranges. Compared to digital transmission, analog transmission is spectrally inefficient and requires extensive frequency planning. Hence, it is important to treat professional audio as a part of the future 5G IoT ecosystem as well.

In Table 2 a summary of above mentioned used cases requirements is shown:

ID	Use case	Latency (ms)	Reliability (PLR)	Update time (ms)	Data size (bytes)	Device density	Communication range (m)	Mobility (km/h)
A	Factory automation	0.25-10	10^{-9}	0.5-50	10-300	0.33-3 dev/m^2	50-100	< 30
A1	Manufacturing cell	5	10^{-9}	50	< 16	0.33-3 dev/m^2	50-100	< 30
A2	Machine tools	0.25	10^{-9}	0.5	50	0.33-3 dev/m^2	50-100	< 30
A3	Printing machines	1	10^{-9}	2	30	0.33-3 dev/m^2	50-100	< 30
A4	Packaging machines	2.5	10^{-9}	5	15	0.33-3 dev/m^2	50-100	< 30
B	Process automation	50-100	10^{-3} - 10^{-4}	100-5000	40-100	10000 dev/plant	100-500	< 5
C	Smart grids	3-20	10^{-6}	10-100	80-1000	10-2000 dev/km^2	A few meters to km	0
D	ITS							
D1	Road safety urban	10-100	10^{-3} - 10^{-5}	100	< 500	3000 dev/km^2	500	< 100
D2	Road safety highway	10-100	10^{-3} - 10^{-5}	100	< 500	500 dev/km^2	2000	< 500
D3	Urban intersection	< 100	10^{-5}	1000	1M/car	3000 dev/km^2	200	< 50
D4	Traffic efficiency	< 100	10^{-3}	1000	1k	3000 dev/km^2	2000	< 500
E	Professional audio	2	10^{-6}	0.01-0.5	3-1000	> 1 dev/m^2	100	< 5

Table 2: Summary of IoT applications in 5G [9]

5.1.2. Mission critical communications in 5G

Mobile networks must meet new demands as human communications changes. The networks must provide significant end-to-end (E2E) latency reduction and higher reliability than those available today. Ultra-reliability is vital for safety. Low latency is crucial to ensure application usability and interactivity whether human-to-human, human-to-machine or machine-to-machine communication.

Minimizing latency and increasing reliability opens up new potential business opportunities for the industry, arising from new applications that simply will not work properly if network delays are too high. Latency determines the perception of speed. Real-time functionality demands the lowest possible delay in the network. Reliability creates confidence in users that they can depend on communications even in life-threatening situations.

These are the proposed 5G use cases requiring Ultra Reliable and Low Latency Communications (URLLC) [10]:

- Autonomous vehicles: Autonomous vehicles are a hot topic for many industry players from car manufacturers, consumers, and insurance companies to governments. Autonomous vehicles can reduce accidents and improve road utilization as vehicles can be driven closer to each other and more safely than human drivers can achieve. Transportation companies can take advantage of autonomous car fleets.

- Augmented/Virtual reality: Augmented Reality (AR) enhances a real-world view with graphics. Real-time information is displayed based on the user's location and/or vision. Virtual Reality (VR) creates a totally new user experience with the user being in a fully immersive environment. The AR/VR device needs to track user movements accurately, process the movement and receiving image, then display the response immediately.
- Industrial control/Automation: Industrial networks have stringent requirements because they require fast machine-to-machine communication and ultra-reliable connectivity. The need for wireless ultra-reliability and virtual zero latency will be driven by uses that include instant optimization based on real-time monitoring of sensors and the performance of components.
- Remote robotics/Surgeries: Remotely controlling robots, rovers, devices or avatars in real time can help us to work safely outside dangerous places. Hospitals can arrange remote robotic surgeries via a customized 5G network as if the surgeon was physically present. For public safety, robots could be sent to work in dangerous situations, such bomb disposal or firefighting.

In Table 3, a summary of above mentioned used cases requirements is shown:

Use case	E2E latency (ms)	Reliability (BLER)	Specialty
Autonomous vehicle	< 5 - 10	$< 10^{-6}$	Mobility
Augmented/Virtual reality	< 5	Less tough	High data rates
Industrial control/Automation	< 0.5	$< 10^{-9}$	Often isolated areas
Remote robotics/Surgery	< 1	$< 10^{-9}$	-

Table 3: Summary of mission critical applications in 5G [10]

5.1.3. ITU-R: IMT-Vision

This Recommendation defines the framework and overall objectives of the future development of International Mobile Telecommunications (IMT) for 2020 and beyond in light of the roles that IMT could play to better serve the needs of the networked society in the future.

IMT for 2020 and beyond is envisaged to expand and support diverse usage scenarios and applications that will continue beyond the current IMT. Furthermore, a broad variety of capabilities would be tightly coupled with these intended different usage scenarios and applications for IMT for 2020 and beyond. The usage scenarios for IMT for 2020 and beyond include [11]:

- Enhanced Mobile Broadband: The demand for mobile broadband will continue to increase, leading to enhanced Mobile Broadband. This scenario will come with new application areas and requirements in addition to existing Mobile Broadband applications for improved performance and an increasingly seamless user experience.
- Ultra-reliable and low latency communications: This use case has stringent requirements for capabilities such as throughput, latency and availability. Some examples include wireless control of industrial manufacturing or production processes, remote medical surgery, distribution automation in a smart grid, transportation safety...
- Massive machine type communications: This use case is characterized by a very large number of connected devices typically transmitting a relatively low volume of non-delay-sensitive data. Devices are required to be low cost, and have a very long battery life.

The key capabilities of IMT-2020 are shown and compared with those of IMT-Advanced:

Capabilities	Area traffic (Mbps/m²)	Network energy efficiency	Connection density (dev/km²)	Latency (ms)	Mobility (km/h)	Spectrum efficiency	User data-rate (Mbps)	Peak data-rate (Gbps)
IMT-Advanced	0.1	1x	10^5	10	350	1x	10	1
IMT-2020	10	100x	10^6	1	500	3x	100	20

Table 4: Comparison of IMT-2020 and IMT-Advanced capabilities [11]

5.1.4. Other 5G use cases

Finally, to sum up the industrial requirements study, some more specific use cases are presented based on METIS-II project [12]. The METIS-II builds on the successful METIS-I project and will develop the overall 5G radio access network design and to provide the technical enablers needed for an efficient integration and use of the various 5G technologies and components currently developed. The most relevant use cases are listed below:

- UC1: Dense Urban Information Society

Besides classical services such as web browsing, file download, email or social networks, we will see a strong increase in high definition video streaming and video sharing. In addition, augmented reality services will be essential in our daily life. For a full experience, information could be fetched from various sources, such as sensors, smart phones, wirelessly connected cameras, databases, servers, and either used locally in the device or sent to be processed in the cloud. Hence, the future mobile and wireless communication system should integrate both highly capable devices and other wireless devices in an efficient way.

- UC4: Massive Distribution of Sensors and Actuators

In order to get the maximum of information from these devices, to increase environmental awareness and better user experience, there is a need for these devices to be able to communicate with other devices and/or with the network. This use case results highly relevant for tracking or monitoring applications.

- UC5: Connected Cars

The use of remote services is also applicable at higher user mobility, e.g. while driving cars or using public transportation. Enabled with higher mobility, both on-the-way workers as well as leisured people can enjoy the benefits of real-time remote computing for mobile terminals. At the same time, the connected car also provides a safe and efficient journey via the communication to its surrounding.

- UC7: Emergency communications

In a place where little mobile or wireless network infrastructure exists, e.g. due to a natural disaster or because this is an inhabited area. Communications are needed instantaneously on demand using regular devices. For instance in case of an earthquake in dense urban environment, survivors below rubble should be able to signal their presence such that they can be found quickly.

Once the main useful use cases for this work are described, below in XX the main characteristics of each use case are listed:

UC	Throughput	Latency	Availability / Reliability	User density	User type	Mobility	Battery life
1	DL: 300 Mbps UL: 50 Mbps	Web browsing & streaming: < 0.5 s. Local or cloud AR: < 5 ms	95% in space and time	Up to 200000 users/km2	Primarily human generated and consumed traffic	3-50 km/h	-
4	From few bytes per day to 1250 B/s	-	99,9% / -	10M device/km^2	Machine	None	At least 10 years
5	Safety: 64-128 kbps RT: DL: 100 Mbps UL: 20 Mbps	Safety: 5 ms E2E RT: < 5 ms E2E	Safety: 100% / 99,999% RT: 99% / 95%	More than 100-1000 per km^2 5 active device at the same time	Machine, human V2V, V2D	Slow speed (3-30 km/h) and vehicle speed (60-250 km/h)	-
7	-	No target	99,9% / -	1 UE per 10m^2	Human (survivor)	None	-

Table 5: METIS-II use cases characteristics [12]

5.2. 802.11 standard family

A relevant portion of industrial communication applications use wireless systems based on standards of the 802.11 and 802.15 families. One of the advantages of 802.11 group is the throughput of Mbps to ranges around hundred meters that provides.

Thus, in this section, two of the main standard versions are going to be analyzed.

5.2.1. 802.11g

The 802.11g version of the standard emerged as an improvement for the existing versions, since the 802.11b standard has a maximum transmission rate of 11 Mbps, and the 802.11a standard only operates in the 5 GHz band. Therefore, the 802.11g variant offers a transmission rate comparable to the 802.11a version (up to 54 Mbps) while allowing operation in the 2.4 GHz band.

Although this standard allows the use of two different transmission techniques (DSSS, Direct-Sequence Spread-Spectrum and OFDM, Orthogonal Frequency Division Multiplexing), throughout this document only OFDM-based transmissions have been worked with. The waveform of a typical OFDM transmission is shown in Figure 2.

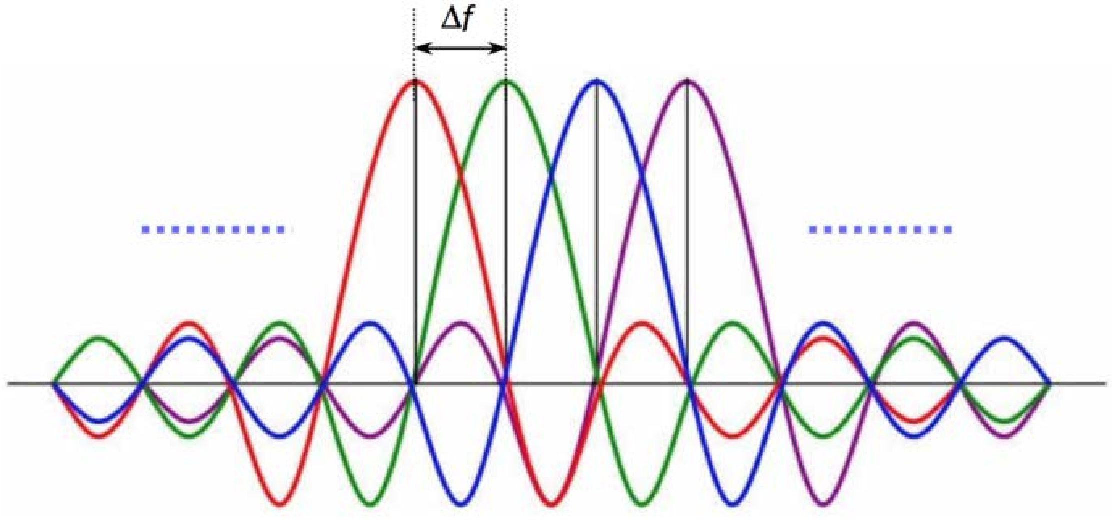


Figure 2: OFDM spectrum

These transmissions are carried out over a 22 MHz bandwidth and a 20 MHz channel separation, where there are 64 carriers: 12 null, 4 pilot carriers and the remaining 48, data carriers. From these data, it is deduced that the space between carriers is 312.5 kHz and the useful bandwidth is 16.6 MHz. Therefore, since the symbol time is the inverse of the space between carriers, 3.2 µs of symbol time are established. In addition to that, 0.8 µs are added to each symbol as guard interval to reduce intersymbol interference, so that the total symbol time is 4 µs.

As for the modulation and coding applied to each transmission, the standard itself defines 8 pre-established transmission modes, as it is shown in Table 6. Those modes vary between BPSK, QPSK, 16-QAM and 64-QAM modulations; to which depending on the case, a Code Rate of 1/2, 2/3 or 3/4 can be applied. Each of the eight available combinations is called MCS (Modulation and Coding Scheme). Due to these configurations, the capacity offered by each of the MCS varies between 6 Mbps (MCS0) and 54 Mbps (MCS7) [5].

MCS	Modulation	Code Rate	Data rate (Mbps)	Bits per OFDM symbol
0	BPSK	1/2	6	24
1	BPSK	3/4	9	36
2	QPSK	1/2	12	48
3	QPSK	3/4	18	72
4	QAM16	1/2	24	96
5	QAM16	3/4	36	144
6	QAM64	2/3	48	192
7	QAM64	3/4	54	216

Table 6: 802.11g transmission modes configurations

Regarding the 802.11g PHY frame, as it is shown in Figure 3, it can be divided into three main sections:

1. Preamble: Its main function is the synchronization of different timers between the transmitter and receiver. It consists of 10 short sequence repetitions and two long ones. Its duration is 16 µs.

2. Header: It is transmitted through the Signal field, and it incorporates the Service field of the data field of the PLCP (Physical Layer Convergence Protocol) frame. It is composed of several subfields: Rate, sending data rate; Reserved, it is reserved for the future, so it is always cero; Length, amount of bytes of the PSDU; (PLCP Service Data Unit) Parity, an even parity bit and Tail, the final six cero bits of the convolutional code.
3. Data: Apart from the MAC frame (PSDU), it contains the Service field, which is used for synchronizing the decoding process; the Tail, which is used to return the convolutional code to 0 state and the Pad bits, which are stuffed bits to use an integer symbol number value.

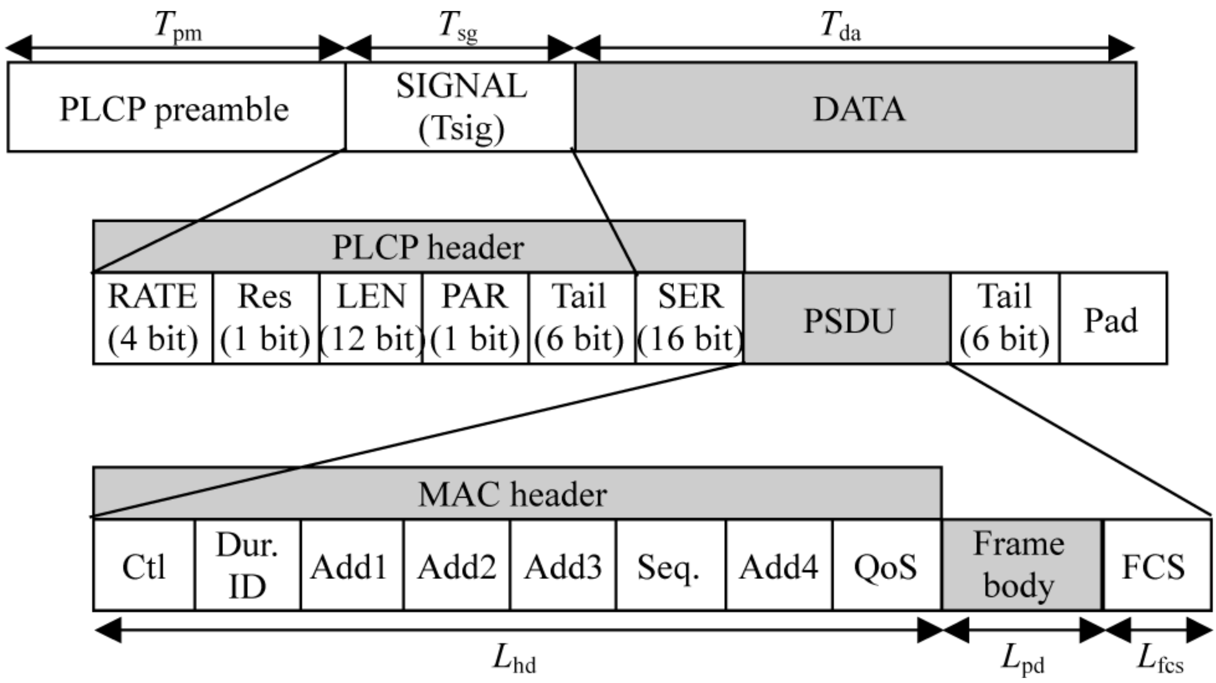


Figure 3: 802.11g PHY/MAC frame format

In order to carry out the Medium Access Control (MAC), as in Ethernet, CSMA (Carrier Sense Multiple Access) protocol is used, which consists in detecting the channel. When it is inactive, it begins to transmit, emitting its complete frame and without listening to the channel in the process, which could cause collisions. To avoid such collisions and data corruption, the 802.11 uses Collision Avoidance (CA) system, in conjunction with CSMA, this consists in counting the channel repeatedly to detect when it is free of other transmissions.

Physically, the CCA (Clear Channel Assessment) is used. CCA is a message indicating both the state and the method of virtual channel sensing. Once it is free, warning messages are sent through it in order to avoid collisions. In case of collisions, there are random waiting times that increase according to the Exponential Backoff algorithm.

On the one hand, in the transmitter side, the input bit stream is encoded using a FEC encoder. In the 802.11g standard case, the OFDM PHY convolutional code is used, which is based on a 6-stage shift register. The output is obtained from two polynomial generators (g_0 = 1011011 and g_1 = 1111001) for a 1/2 code rate. Whether higher code rates are needed, some of the encoded bits are omitted.

On the other hand, in the receiver side, for each of the MCS value, the PER-SNR (Signal-to-Noise Ratio) curves have been calculated in order to relate the received Signal to Noise Ratio with the probability that this packet has to be erroneous. These curves are shown in Section 6.2.2.2. There can be highlighted that the thresholds for 0.1 PER vary depending on each MCS, from 0.8 dB of the MCS0 to 18 dB of the MCS7.

Finally, it is important to underline the interoperability both forward and backward of the 802.11g standard (compatible with 802.11b and with 802.11n). In this last version of the standard, there is a mode called Legacy Mode, where frames are transmitted in the legacy 802.11a/g OFDM format, in order to guarantee interoperability. Therefore, the proposal presented in this document is equally applicable to some of the transmission modes of the 802.11n standard.

5.2.2. 802.11n

The 802.11n standard appeared as a version of the existing 802.11g version in order to offer higher throughput data rates. Although it conserves many characteristics of its forerunners, such as for example the CSMA/CA access to the medium, it also incorporates significant improvements achieved through physical velocities of up to 600Mbps.

The main reason to achieve those high theoretical throughputs is by using MIMO. This standard provides Spatial Division Multiplexing (SDM), which spatially multiplexes multiple independent data streams, transferred simultaneously within one spectral channel of bandwidth. Although this standard allows the use of that different transmission technique, throughout this document only SISO (Single Input Single Output) transmissions have been worked with.

There are two operating modes in the 802.11n standard, one for High-Throughput (HT) solutions and another one for Non-HT solutions, Greenfield and Mixed Mode, respectively. Greenfield mode can only be used when no legacy devices exist in the network. An 802.11n device using Non-HT mode sends every packet in the old 802.11a/g format so that the other devices can understand it. That device must use 20 MHz channels and none of the new HT features.

These transmissions are carried out over a 20 MHz bandwidth, where there are 64 carriers: 8 null, 4 pilot carriers and the remaining 52, data carriers. From these data, a carrier spacing of 312.5 kHz and a useful bandwidth of 17.8 MHz is deduced. Therefore, since the symbol time is the inverse of the space between carriers, the symbol time should be 3.2 µs. In addition, 0.8 µs are added to each symbol as guard interval to reduce intersymbol interference. In total, the overal symbol time is 4 µs. As an option, a 40 MHz bandwidth could be used, which enhances the overall offered throughput [13].

MCS	Modulation	Code Rate	Data rate (Mbps)	Bits per OFDM symbol
0	BPSK	1/2	6	24
1	QPSK	1/2	12	48
2	QPSK	3/4	18	72
3	QAM16	1/2	24	96
4	QAM16	3/4	36	144
5	QAM64	2/3	48	192
6	QAM64	3/4	54	216
7	QAM64	5/6	60	240

Table 7: 802.11n tranmission modes configurations

As for the modulation and coding applied to each transmission, the standard itself defines 8 pre-established transmission modes. Those modes vary between BPSK, QPSK, 16-QAM and 64-QAM modulations, to which depending on the case, a Code Rate of 1/2, 2/3, 3/4 or 5/6 can be applied. Each of the 8 available combinations is called MCS (Modulation and Coding Scheme). Based on those configurations, the capacity offered by each of the MCS varies between 6 Mbps (MCS0) and 60 Mbps (MCS7). All the available MCS values for the Non-HT modes and each capacity are shown in Table 7.

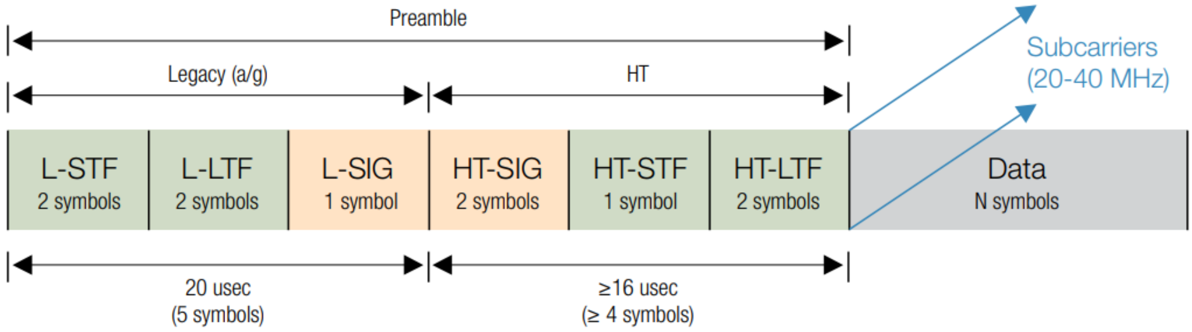


Figure 4: 802.11 Mixed Mode PHY frame format

The 802.11n PHY frame (Figure 4), it is divided into three sections:

- Non-HT Legacy: L-STF, L-LTF and L-SIG are backward compatible with 802.11a/g devices. L-SIG field contains rate and length values in order to inform legacy systems.
- HT Mixed Mode: HT-SIG value indicates MCS, length and specific parameters. HT-STF and HT-LTF are used for synchronization and channel estimation on HT bandwidth. Additional HT-LTF symbols can be included for MIMO cases.
- Data: Apart from the MAC frame (PSDU), it contains pilot subcarriers, using only BPSK, which are used to note phase and amplitude variation over the burst.

Regarding some of the similarities with the 802.11g standard, it should be underlined the used of the CSMA/CA as the MAC protocol, and the use of CCA for the virtual channel sensing.

On the one hand, one of the responsible for the throughput improvement and for the SNR threshold value reduction in comparison with the 802.11g standard are the FEC implemented, the LDPC (Low Density Parity Check) codes specifically. The IEEE 802.11n wireless standard involves three sub-blocks (27, 54, and 81 bits) and four code rates. Hence, 12 different Z x Z sparse matrices can be selected.

On the other hand, in the receiver side, for each of the MCS value, the PER-SNR curves have been calculated in order to relate the received Signal to Noise Ratio with the probability that this packet has to be erroneous. These curves are shown in Section 6.3.2.2 for both an AWGN and industrial channels. Moreover, results have been compared with the Shannon limit and a gap close to 2 dB is observed. Thresholds for guaranteeing a PER of 10^{-2} vary depending on each MCS and range from 1.8 dB (MCS0) to 16.9 dB (MCS7).

5.3. Non-Orthogonal Multiplexing Access (NOMA)

General speaking, NOMA consists on a signal ensemble composed of several layers, each one taking a portion of the total power delivered by the transmitter. Each of the layers will have different robustness, decoding thresholds and capacities as a function of the modulation and coding choice for each layer but also depending on the power distribution to each one of the layers. The power distribution is normally described by the parameter Δ (injection level, measured in decibels). The multiple layer signal concept for two services is shown in Figure 5 and the general frequency domain NOMA signal is expressed as:

$$x_{NOMA}(k) = x_{S1}(k) + g \cdot x_{S2}(k) \qquad (1)$$

where $x_{S1}(k)$ and $x_{S2}(k)$ are the two data streams combined into the NOMA ensemble $x_{NOMA}(k)$ and k is the subchannel index. The injection level g defines the linear power allocation ratio between layers. In practice, this parameter is usually referred to in its logarithmic for ($\Delta = 10 \log(g)$).

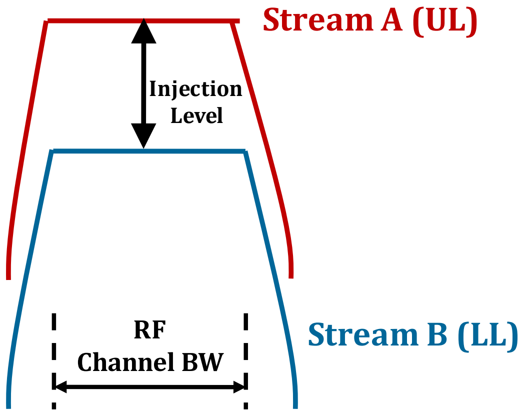


Figure 5: Non-Orthogonal Multiplexing schemes

The idea of multiple signals on the same channel was described decades ago by information theory papers under the name *superposition coding* [14]. However, the application of the concepts into real equipment has been only feasible lately. One of the drivers for feasibility is the developments in error coding and specifically, the remarkable advances in the field of LDPC codes [15]. The latest LDPC codes performance is closer than half a dB from the Shannon curve. Translated into NOMA architecture, it means that the upper layer service can be decoded for very low SNR values. The second driver for feasibility is the newly implemented signal cancellation structure proposed in [16] that, taking advantage of the structure of the LDPC matrix proposed in [17] simplifies the complexity of the receiver significantly.

For instance, in 2017, the ATSC 3.0 television standard has approved a low-complexity solution based in LDM (Layered Division Multiplexing) for the efficient delivery of low capacity and high capacity services in the same RF channel. LDM has undergone intense research work during the last years under the umbrella of the standardization process of the next generation broadcast standard ATSC 3.0 [18][19].

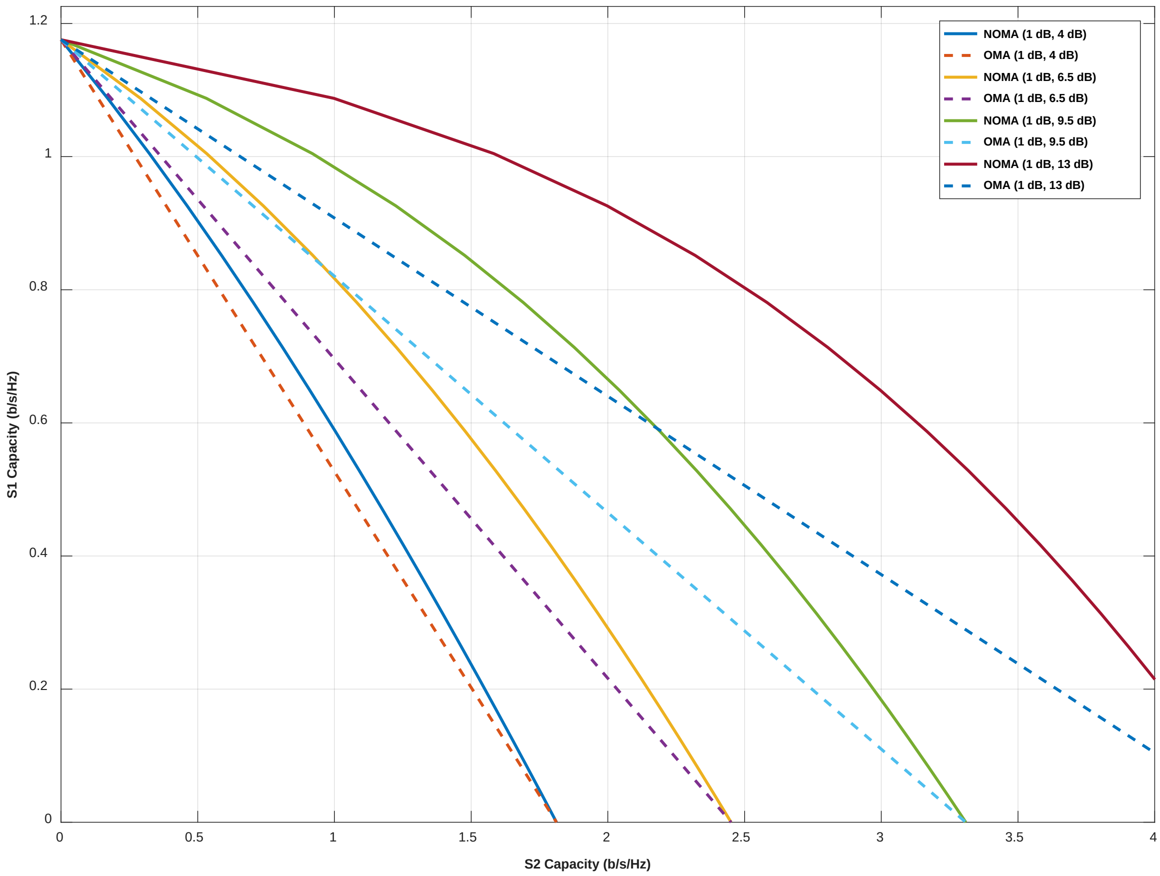


Figure 6: Theoretical NOMA/TDM comparison

In Figure 6, there is a graphical comparison of the spectral efficiency of NOMA and traditional TDM/FDM schemes from the information theoretic point of view when two services are delivered in the same time and frequency resources [20]. The solid lines represent the spectrum efficiency in terms of bps/Hz for the NOMA based solutions, where the dashed lines stand for the TDM/FDM services. Each pair of curves describe the optimum capacity for a two different SNR thresholds. For instance, the solid blue (NOMA) and the dashed orange (OMA, Orthogonal Multiple Access) compared the obtained spectrum efficiency when the low-throughput SNR is 1 dB and the high-throughput is 4 dB respectively. In this case, the maximum gain is about 0.1 bps/Hz depending on the required bitrates. Nevertheless, if the pair of curves for (1dB, 13 dB) is studied, the overall gain offered by NOMA can be up to 1 bps/Hz.

In practice, NOMA will provide spectral efficiency advantages in cases where the services have different robustness requirements. This involves different code puncturing and possibly different interleaving lengths on each layer. For practical purposes, any interleaving block as well as the channel coding intervals will require careful design.

Last, but key for system feasibility in industrial environments, processing time and resource requirements at the receiver require special attention. Industrial communication systems are typically rolled out for supervision and control purposes [3][10] where security, reliability and delay will be critical design constraints. LDM directly addresses security and reliability based on close to zero and even negative reception thresholds. Flexible configuration of layers also is an advantage for increasing the security of the physical layer. On the contrary, the cancellation associated to lower layer decoding involves additional processing latency on the receiver. The specific error coding technique is the key factor to this respect. Some reference works are available in the literature. In [21], the latency associated to large LDPC codes was analyzed. The results show that the number of iterations of the LDPC decoding algorithm remains below 5 for SNR values below 4-5 dB, making the associated decoding time not relevant on the overall OFDM receiver processing time budget, mostly influenced by MAC operations. Nevertheless, it should be noted that time requirements cannot be described on a general basis and each application scenario requires a thorough analysis of the control-cycle vs. receiver processing time. This document focuses on system feasibility and potential reliability/throughput advantages over TDM/FDM systems.

6. Methodology

In this section, the methodology followed in the elaboration of the project together with the results obtained during development is presented.

First, the general architecture of the simulation process is described. The methodology of dual simulation carried out is explained. In the following section, the process followed for the simulation of the PHY layer is detailed. First, the simulation model used is described and then the results obtained both theoretically and by simulation. Finally, the work done on the MAC layer is detailed, which describes the simulation system used, the use case designed and the results obtained.

6.1. System

In order to validate NOMA as the physical layer of the 802.11g/n standard, a dual simulator has been developed, consisting of a network simulator and a mathematical simulator. The first is used to implement a complete communications network, while the second is used to evaluate the robustness of the system against the chosen channel. In this case, Matlab and OMNeT++ have been used.

In a first step, using the evaluation in Matlab, PER curves are obtained according to the reception SNR, which take into account all the effects of the channel and the characteristics of both transmission and reception.

Once these curves are obtained, they are loaded in OMNeT++ and whether a packet is received or not based on the SNR obtained by the receivers, (proportional to the distance between the devices that communicate) is evaluated. To do this, the corresponding PER point is extracted from the curve, a random number generation function is executed, and if the value is below the PER value, the package is assumed to be erroneous; otherwise is assumed that the package has been received correctly.

In order to carry out the recently exposed methodology, a version of the proposed model that combines NOMA with the 802.11g/n standard has been developed in OMNeT++.

6.2. NOMA-based 802.11g

This section details the steps followed in the integration of NOMA as the physical layer of the 802.11g standard and the results obtained.

6.2.1. Theoretical comparison

Industrial automation is one of the key scenarios where Wireless Sensor Networks (WSNs) are applicable jointly with NOMA technologies for monitoring and controlling plants and equipment. It will normally operate on low- power signals and are highly susceptible to interference. Therefore, providing that the 802.11g version is implemented (or the non-high-throughput mode of the 802.11n) the most robust MCS combination, that guarantees the required bitrate, will be always present in order to deal with the mission-critical communications. The enhance layer services capacity will vary depending on the target, but it is expected that the highest SNR value will be about 20 dB.

802.11g + NOMA (two layers) vs. 802.11g								
	NOMA		Robust Service (66%)		Robust Service (50%)		Robust Service (25%)	
	Data rate	SNR	Data rate	SNR	Data rate	SNR	Data rate	SNR
CL 1	6 Mbps BPSK 1/2	3.0 dB	6 Mbps BPSK 3/4	3.6 dB	6 Mbps QPSK 1/2	4.0 dB	6 Mbps 16QAM 1/2	9.5 dB
	IL = -7 dB		EL (33%)		EL (50%)		EL (75%)	
EL1	12 Mbps QPSK 1/2	11.97 dB	12 Mbps 16-QAM 3/4	13 dB	12 Mbps 16-QAM 1/2	9.5 dB	13.5 Mbps QPSK 3/4	6.5 dB
EL 2	24 Mbps 16-QAM 1/2	17.54 dB	N.A N.A	N.A	24 Mbps 64-QAM 2/3	17 dB	27 Mbps 16-QAM 3/4	13 dB
EL 3	36 Mbps 16-QAM 3/4	20.79 dB	N.A N.A	N.A	N.A N.A	N.A	40.5 64QAM 3/4	18.3 dB

Table 8: Theoretical threshold calculation for NOMA-based 802.11g

In Table 8, three different uses cases are considered. These cases cover a set of representative service configurations for the industrial environment. In all the cases, the CL (Core Layer) has a minimum required throughput of 6 Mbps. This throughput is expected to guarantee the critical communications bitrate several clusters of sensors.

Regarding the best effort services, Table 8 describes three different enhance layer configurations aiming at covering different multimedia services ranging from 12 to 36 Mbps. In general, the MCS values for the TDM case has been selected in order to offer the capacity that is closer to the decided value. Even though, taking into account the numerology of the 802.11 family is it not possible to match perfectly those values.

Whereas the TDM based services thresholds are directly obtained from the values presented in [22], the NOMA based theoretical thresholds are calculated applying the formulas presented in [23].The injection level for the NOMA case is fixed to -7 dB and the TDM shared resources are (66.66%- 33.33%, 50%-50%, 25%-75%).

The first important outcome is that the non-orthogonal solution is the only one capable of granting SNR thresholds below 3 dB. Second, TDM based services require increasing the SNR value of the critical service up to 9.5 dB, providing that the EL (Enhanced Layer) is about 40 Mbps. Third, the more asymmetrical the services are the more noticeable the NOMA gain is. Nevertheless, it must be noted that when both services capacity requirement and SNR threshold is similar the NOMA gain is not so high. For instance, when the CL layer is offering 6 Mbps and the EL 12 Mbps, the TDM based solution (%50-50%) is also a good alternative.

Even though, as a general rule the asymmetry of services proposed NOMA based alternatives a very promising solution.

6.2.2. PHY

First, the physical layer has been implemented for one and two layers, i.e., only the 802.11g standard and NOMA-based 802.11g.

6.2.2.1. Simulation setup

In this project, a combination of 802.11 and NOMA is proposed as a solution to address the challenges of industrial wireless environments. In particular, a modification of the 802.11g standard is proposed. A new transmitter-receiver architecture is designed using power based NOMA as the multiplexing solution, which can be understood as a low complexity NOMA case. Consequently, the architecture proposed in this project keeps receiver complexity as low as possible.

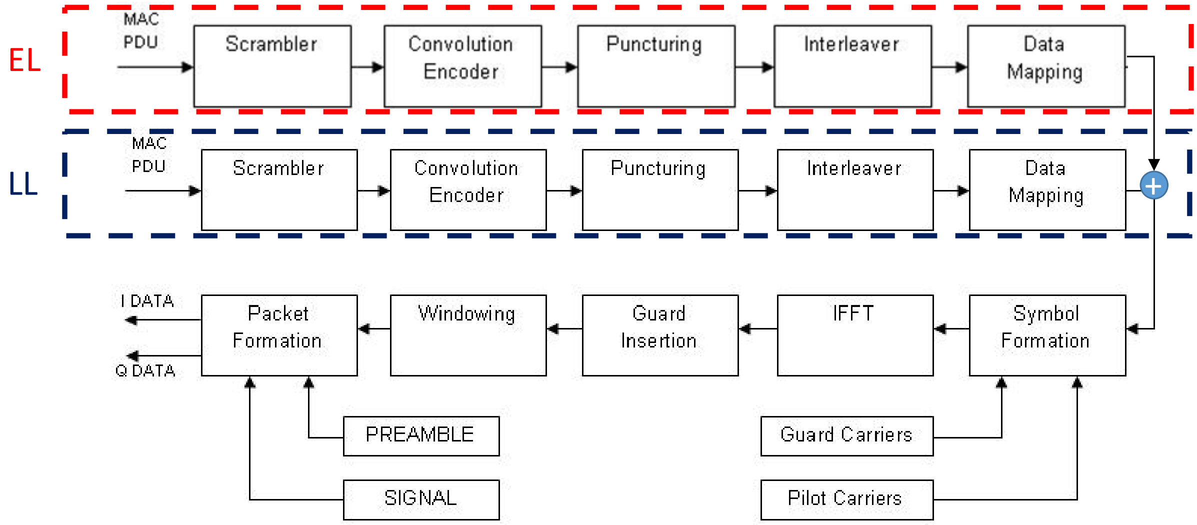


Figure 7: NOMA-based 802.11g transmitter

The transmitter side is composed of an adaptation module that prepares data for the error coding stage (Figure 7). A proper choice of the data overlapping is highly important for efficient and simple receiver implementation. For the sake of simplicity and compatibility with further experiments on the 802.11 family, Forward Error Correction (FEC) scheme is the same proposed in IEEE 802.11g/n [5]. If the system uses OFDM waveforms and the framing structure of each one of the layers are synchronized, the receiver complexity and latency remains acceptable.

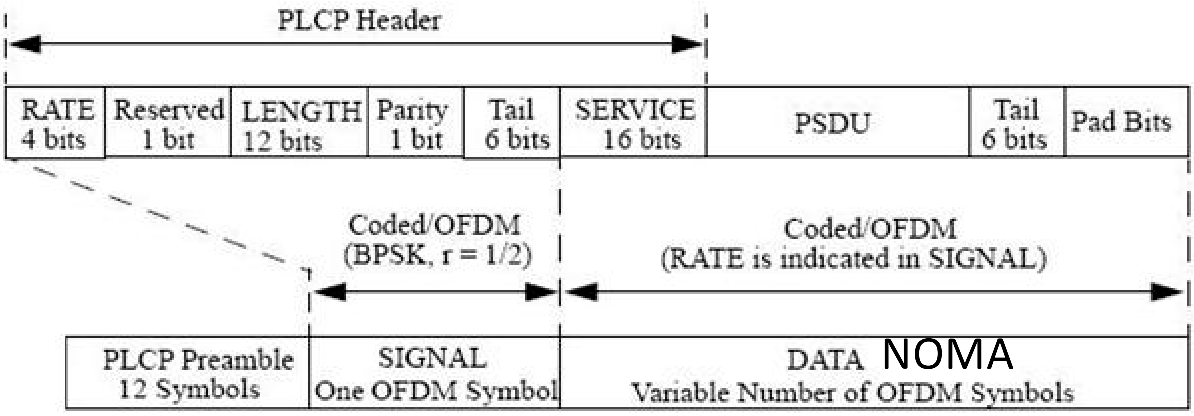


Figure 8: NOMA frame structure

The mapping and framing stage are inherited directly from 802.11g Modulation and Coding Schemes (MCS). The only difference is that after mapping, both services are combined into a single stream. The next stages performed in frame base are equivalent for both services as they are one ensemble. The final physical waveform is PHY packets composed of a preamble and a data field (Figure 8). The detailed structure of the PHY packet is maintained as defined in 802.11g (see Section 5.2). However, there is one additional requirement: the packet length of the enhance layer service is selected in order to match the same number of symbol per frame that the core layer service. It must be taken into account that the maximum length of the PSDU is 4095 bytes.

Due to the proposed transmitter structure, the first modules of the NOMA receiver are identical to existing 802.11g receivers. After RF conditioning, the carrier and time synch stages prepare the input for channel and equivalent noise estimation, operation performed based on the information conveyed in L-LTF and L-SIG sections. The L-SIG also helps in detecting the MCS choices of the received PHY packet. All these information pieces aid on OFDM symbol recovery and subcarrier.

After equalization, the CL decoding is carried out by decoding, demapping and interleaving modules. This CL bit stream will be available for all sensor/actuators in the service area. If the available SNR permits, the cancellation and enhance layer decoding will be the next steps. The cancellation will depend on the injection level value, the channel estimation metrics and the CL itself. Once the CL has been cancelled the EL decoding, demapping and interleaving are straightforward.

At the receiver, the NOMA signal on the *k*-th channel can be expressed can be expressed as,

$$y_{NOMA}(k) = \left(x_{S1}(k) + g \cdot x_{S2}(k)\right) \cdot h(k) + n(k) \qquad (2)$$

where $y_{NOMA}(k)$ is the received symbol, *h* (*k*) is a static multipath channel and *n* (*k*) is the sum of AWGN noise and other additive interference. A key step in CL decoding and subsequent cancellation is equalization. Previous research characterized the impact of the channel estimation error into the system performance and it was found that low SNR thresholds on the CL make detection very robust, even in challenging propagation scenarios [24].

Once the CL has been decoded, a signal cancellation algorithm must be implemented in order to access to the EL. In this work, it is proposed to use the H-SIC cancellation scheme, because it offers a very good trade-off between complexity and performance. The decoded CL is coded and modulated again, and then, it is removed from the equalized NOMA signal. Afterwards, the received can be expressed as:

$$x_{S2}(k) = g \cdot x_{S2}(k) + i(k) + n(k) \qquad (3)$$

where i(*k)* is the error cancellation due to the channel estimation error. Eventually, the rest of the receiving blocks are the same as the ones used for the core layer decodification.

In order to do so, a complete transmitter and receiver chain fully compliant with the 802.11g has been implemented. Afterwards, several modifications have been introduced in the simulation chain in order to make it possible to multiplex services in NOMA basis.

First, at the MAC layer the two different layers PSDU packet length is adjusted in order to assure that they will require the same number of symbols per frame. Consequently, at the mapping block a NOMA approach could be used, and thus, the receiver architecture will be simplified. In general, the EL PSDU length should be a higher than the EL packet. For instance, if the PSDU length is 1000 bytes for the Core Layer, at least 2000 bytes are required for the EL packet. Afterwards, the transmitter block has been modified according to Figure 7 in order to be able to power multiplex two different services. The two layer data are ensemble after the mapping block according to the selected injection level. As this is a comparative study, firstly, the less challenging AWGN channel is implemented as a propagation channel, and, secondly, an industrial channel model with Non-Line-Of-Sight (NLOS) condition and 29 ns rms delay spread [25].

At the receiver, a HARD-SIC cancellation algorithm is added to the well-standardized 802.11g receiver. The synchronization and channel estimation are considered perfect.

The performance is evaluated through the Packet Error Rate (PER). In particular, each SNR value more than 2000 packet are tested. A PSDU packet is considered erroneous if any of the bits are decoded incorrectly. Finally, it must be noted that the simulation step is 0.1 dB.

6.2.2.2. Results

First, the single layer/service simulations are studied. The main idea is to test the performance and compared it trustworthy references in order to prove that the simulation chain has been successfully built.

The results are gathered in Figure 9. The PER values are obtained for the eight different MCS schemes available in the 802.11 g standard. It can be seen that the obtained results at a 0.1 PER are in line with those presented in the literature [22]. The SNR ranges from 1 dB to about 20 dB depending on the selected modulation and coding scheme. Based on the reviewed literature the MCS 0 is the only one that guarantees the minimum robustness requirements, whereas from MCS1 to MCS4 can be implemented for integrating audiovisual services within the 802.11 communications chain.

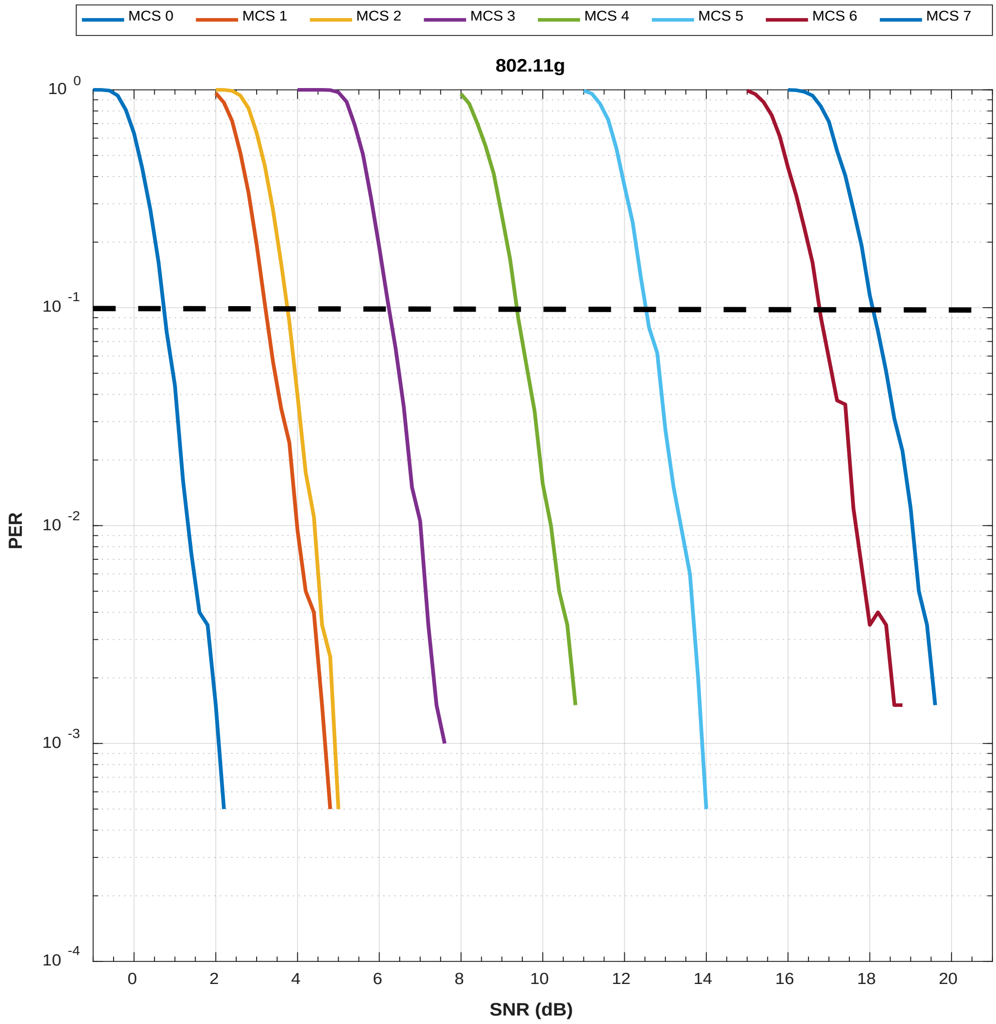


Figure 9: 802.11 g one layer thresholds

Once that the platform has been validated the next step is to test the NOMA proposal and check that the results presented in Table 8 are in line with the simulation results. In fact, the configuration presented in Table 8 are simulated for the 802.11g modified simulation chain.

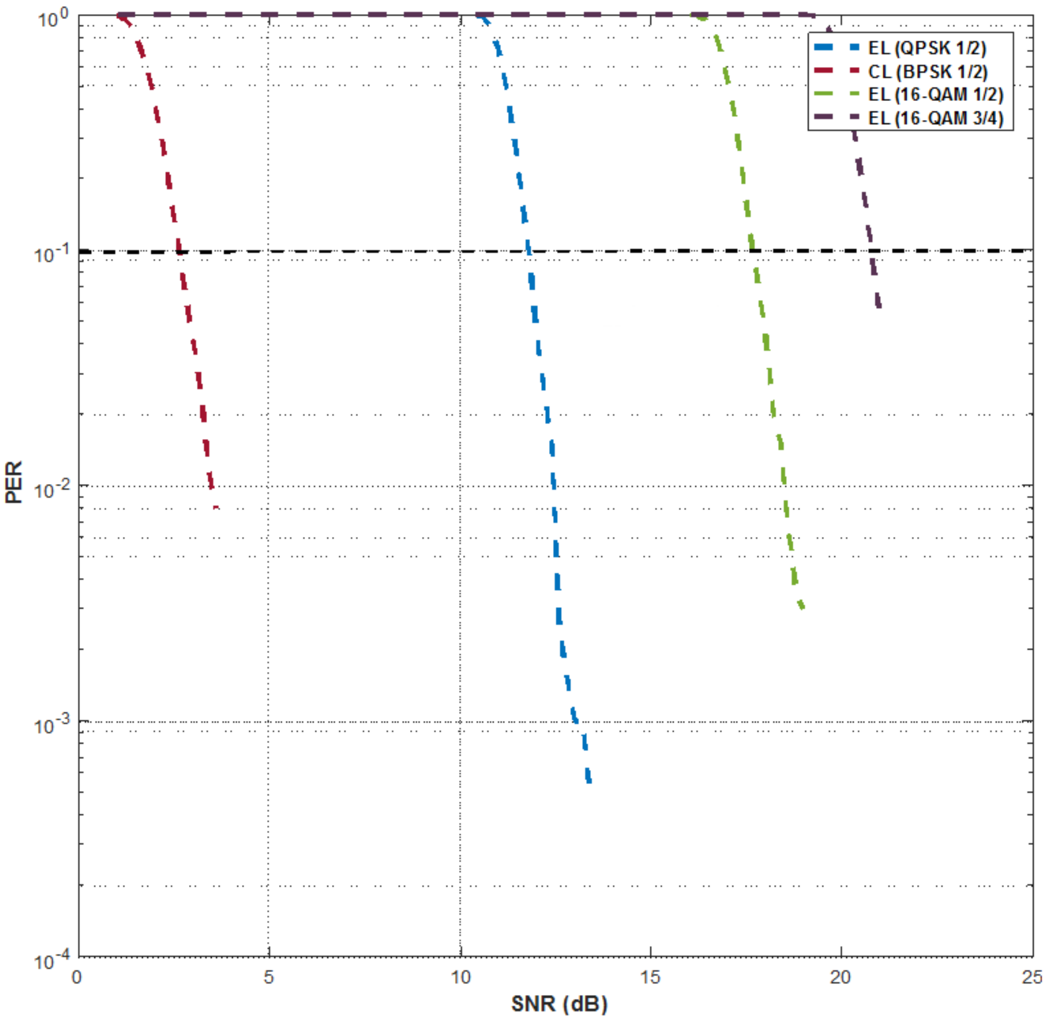


Figure 10: NOMA-based 802.11g two layer thresholds

In this case, the channel estimation and synchronization is also considered ideal. It must be noted that in all cases, the simulated SNR thresholds at 0.1 PER (the dashed black line in Figure 10) are very well aligned with the theoretical values gathered on Table 8.

6.2.3. MAC

Once PHY layer is completely validated, it is time to measure the capacity of the MAC layer.

6.2.3.1. Simulation methodology

To evaluate the MAC level reliability of the elaborated proposal described in the previous lines, a methodology based on the OMNeT++ package simulator has been followed.

First, a model to simulate transmissions of the proposed NOMA-based 802.11g standard is used, which has been entirely developed. This simulator takes as input the curves obtained in the previous section. In these curves, the PER value is shown for each SNR value in 0.1 dB steps for each of the MCS available in the standard. The simulator, based on the instantaneous SNR, obtains the predicted PER value and determines in reception whether the packet being evaluated is erroneous or not.

Simulations are launched with a simulation time limit that is detailed in the next section. Once the period has ended, OMNeT++ stores for each of the network device the number of received packets, the number of sent packets and the number of lost packets, among others. From there, the results shown in Section 6.2.3.3 are calculated.

6.2.3.2. Use case

The simulation methodology proposed in the upper lines must be implemented in a specific scenario and under specific characteristics. Therefore, in this section the use case implemented in the simulations is detailed, always taking into account the industrial communications requirements for FA and PA use cases established in Section 5.1.1.

The simulation case choice is a manufacturing plant. For this aim, the network architecture is composed of a central node (Access Point, AP) located in the center of the plant and 20 slave nodes distributed randomly along the facility. Devices usually related to the industry in IWSN networks, as sensors or actuators, are represented by slaves. In this case, slaves are both traffic receivers and transmitters. However, the AP is the master node of both the architecture and the synchronization, and distributes information to all the devices connected in the network using 1000 Bytes packets. The traffic distributed by devices can be classified into two different types:

- Real-Time (RT): Traffic with strict requirements. High robustness required, related to low MCS schemes. Loss intolerant and non-delay tolerant. High priority traffic, such as, alarms or synchronization information is represented.
- Best effort (BE): Traffic with less strict requirements. High capacity, related to high MCS. Loss and delay tolerant. Low priority traffic, such as office services or complementary information is represented.

Time schedules are a key factor for comparing different medium access techniques. That is why, in this case it is necessary to specify them in order to compare TDMA-based 802.11g standard with the NOMA-based one. For the TDMA system, traffic of a single type is transmitted in each of the slots, as it is shown in Figure 11. On the other hand, for the NOMA system, in each time slot both types of traffic are transmitted, placing the RT traffic in the upper layer and the BE traffic in the lower layer, as it is shown in Figure 12. In this way, while in the TDMA system, the time domain is shared between both traffics, in the NOMA system 100% of the time is used by both types of traffic.

In addition to the temporary distribution, a distinction must be made between downlink (DL), from AP to Slave, and uplink traffic (UL), from Slave to AP, and RT and BE traffic. Hence, four traffic types that have to be organized. In TDMA systems, the superframe is divided into two main blocks, the RT traffic transmission slots and the BE traffic block. Regarding the RT traffic, the medium access is deterministic, so that a specific time is dedicated to each slave, consisting of two slots, one for DL traffic and the other for UL traffic. The length of each of these spaces is related to the airtime of the packet and it varies depending on the transmission mode used. Once the communication with all the slaves has been carried out, the space for the BE traffic transmission starts. In this case, the access is achieved by contention, and the duration of this traffic block (common for the 20 slaves and the AP) is according to the time distribution established in Table 9, for instance, in the cases of TDM 50% - 50%, the duration of the BE traffic block is equal to the RT communication with the 20 nodes. An example of the TDMA system time distribution is shown in Figure 11.

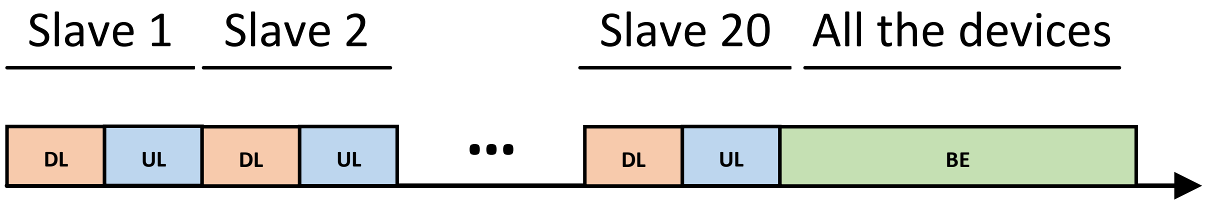


Figure 11: TDMA time schedule representation

On the contrary, in NOMA systems, traffic has to be restructured. In this way, the superframe is only divided by nodes, and during each of these divisions, there is a complete communication between the AP and the respective slave. In this case, the medium access is completely ordered for both RT and BE traffic, since they are transmitted in the same time slot using the upper and lower layers, respectively. The slot size for this technique is equal to the amount of time the upper layer package is in air, and, so, the amount of data transmitted in the lower layer is adapted to match the upper layer air time. An example of the NOMA system time distribution is shown in Figure 12.

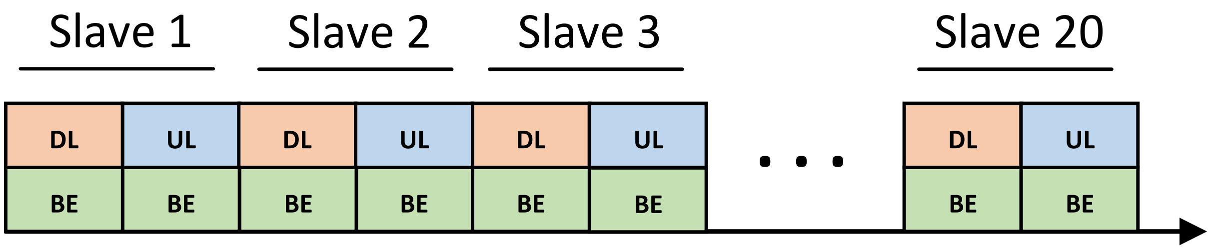


Figure 12: NOMA time schedule representation

According to each type of traffic requirements, a specific data rate has been assigned. In the case of RT traffic, a requirement of 6 Mbps has been assumed, and for the BE traffic two possible scenarios has been taken into account, 12 Mbps and 24 Mbps requirements. In the case of NOMA based systems, 36Mbps has also been taken into account, because due to the flexibility it offers, unlike TDMA, a greater capacity can be offered. Because of the temporary distribution made in TDMA, to offer the same capacity as NOMA for a service, higher MCS should be used, assuming an important penalty in reliability. In Table 9, a summary of the cases that have been simulated for both TDMA and NOMA is shown.

Channel	ID	Traffic Type	% Time	IL (dB)	MCS	T_{Cycle} (ms)
AWGN	TDMA (I)	RT	66	-	1	54.48
		BE	33		5	
	TDMA (II)	RT	50	-	2	54.72
		BE	50		4	
	TDMA (III)	RT	50	-	2	54.72
		BE	50		6	
	NOMA (I)	RT	100	-7	0	54.64
		BE	100		2	
	NOMA (II)	RT	100	-7	0	54.64
		BE	100		4	
	NOMA (III)	RT	100	-7	0	54.64
		BE	100		5	
IND	TDMA (I)	RT	25	-	4	56.32
		BE	75		3	
	TDMA (II)	RT	50	-	2	54.72
		BE	50		4	
	TDMA (III)	RT	50	-	2	54.72
		BE	50		6	
	NOMA (I)	RT	100	-9	0	54.64
		BE	100		2	
	NOMA (II)	RT	100	-9	0	54.64
		BE	100		4	
	NOMA (III)	RT	100	-9	0	54.64
		BE	100		5	

Table 9: MAC level simulation configurations

Due to the cycle time length, shown as well in Table 9, the update time requirements that are established for industrial communications are met.

In order to obtain as much realistic results as possible, twenty simulations have been carried out with each configuration, varying the seed in each of them to obtain different initial equipment position distributions and, so, different propagation cases will appear.

6.2.3.3. Results

Once the use case for the validation proposal is presented, results are shown distinguished by the channel type in Table 10 and Table 11.

ID	AWGN Channel					
	RT			BE		
	Send (M)	%Loss	Data Rcv. (MB)	Send (M)	%Loss	Data Rcv. (MB)
TDMA (I)	2.64	0.0342	2642.26	4.76	62.4289	1787.52
TDMA (II)	2.63	0.1241	2628.29	4.93	29.5249	3477.37
TDMA (III)	2.63	0.1241	2628.29	9.28	83.7131	1510.81
NOMA (I)	2.64	0.0003	2635.39	5.27	59.6856	2124.89
NOMA (II)	2.64	0.0003	2635.39	10.54	88.6357	1226.44
NOMA (III)	2.64	0.0003	2635.39	15.81	93.7671	985.57

Table 10: MAC level results for AWGN channel

ID	Industrial Channel					
	RT			BE		
	Send (M)	%Loss	Data Rcv. (MB)	Send (M)	%Loss	Data Rcv. (MB)
TDMA (I)	2.56	25.1300	1914.28	5.69	28.7281	4054.57
TDMA (II)	2.63	2.4319	2567.56	4.93	47.7210	2579.49
TDMA (III)	2.63	2.4319	2567.56	9.28	87.9091	1121.58
NOMA (I)	2.64	0.5185	2621.74	5.27	77.9109	1164.27
NOMA (II)	2.64	0.5185	2621.74	10.54	93.6699	667.29
NOMA (III)	2.64	0.5185	2621.74	15.81	96.6956	552.51

Table 11: MAC level results for industrial channel

First, for the AWGN channel simulations, it should be noted that NOMA based RT services are more robust than TDMA based ones. In fact, NOMA based architectures improve TDMA results by three orders of magnitude, reducing losses of 10^{-3} down to losses of 10^{-6}. This implies a remarkable increase in the communication reliability. However, for BE services result trend is opposite. In this case, services based on NOMA have a higher error rate.

Secondly, in the industrial channel case, it can be seen that although the results generally contain a greater number of losses, because the necessary thresholds are higher, the trend remains. That is, the NOMA-based systems offer a large increase in the robustness of the RT services, five times less losses than the more robust TDMA results, and a greater number of losses in the BE services.

It should be also highlighted that despite the good results that the TDMA (I) system has for the industrial channel for BE services, the high rate of errors in the RT services makes it unusable. For this reason, a compromise solution between services of maximum tolerable error rate is required. For example, for cases in which an ultra-robust service is required, services such as the one described in NOMA (I) have to be considered, since virtually no error rates are obtained, and a net information rate is received in BE services, that could cope with those received with TDMA systems.

In addition, it is important to highlight the role played by each of the services and the requirements they have. Therefore, it is extremely important to increase the robustness of the RT services; for instance, if synchronization information is send by RT services, a failure in the transmission can result in the loss of an entire superframe, that is, that the packet losses in the information of synchronization directly affect the BE information.

Although it was not one of the main objectives, due to the temporary reorganization of the services, a considerable gain in determinism has been obtained for BE services. Using NOMA techniques, as BE services are transmitted in the lower layer and they are aligned with RT services, which need high reliability, it is much easier to determine the timing of the transmission and the reception of each BE package, and therefore, it is easier to predict their latency, among other parameters.

Generally speaking, results are not as good as expected. It is true that an increase in the reliability of the RT traffic is obtain, whereas the BE services are almost useless. The main reason for these results appears in [20]. There is a big difference between the theoretical SNR obtained from Shannon limit and the real SNR obtained by using convolutional codes in these simulations. That difference affects straightaway to the performance of NOMA. Hence, in the next section, LDPC codes are going to be used as error correction codes in order to get closer to Shannon limit and improve the performance of NOMA in comparison with TDMA systems.

6.3. NOMA-based 802.11n

Taking into account the results obtained in the previous section, an improvement towards better reliability is possible. First, the convolutional codes from the NOMA systems have been replaced with LDPC codes. In this case, the performance comparison has to be made with 802.11n standard, which supports LDPC codes. This way, thresholds should be near Shannon limit and results should improve. Second, simulated packet length has been reduced in order to reduce each simulation cycle time to get more realistic scenario in terms of requirements.

6.3.1. Theoretical comparison

As it has been done in Section 6.2.1 for 802.11g standard, in this Section a theoretical overview of the thresholds will be done.

NOMA				TDM /FDM			
CASE A CL (6 Mbps) EL (12 Mbps)	NOMA (IL =-4dB)			CASE A CL (6 Mbps) EL (12 Mbps)	CL (%50) / EL (% 50)		
	MCS	AWGN	INDUSTRIAL		MCS	AWGN	INDUSTRIAL
	BPSK 1/2	1.0	1.8		QPSK 1/2	1.3	1.9
	QPSK 1/2	6.8	7.4		16-QAM 1/2	6.7	7.5
CASE B1 CL (6 Mbps) EL (24 Mbps)	NOMA (IL = -6,5dB)			CASE B1 CL (6 Mbps) EL (24 Mbps)	CL (%50) / EL (% 50)		
	MCS	AWGN	INDUSTRIAL		MCS	AWGN	INDUSTRIAL
	BPSK 1/2	-0.3	0.5		QPSK 1/2	1.3	1.9
	16 QAM 1/2	14.1	14.9		64-QAM 2/3	14.3	15.2
CASE B2 CL (6 Mbps) EL (24 Mbps)	NOMA (IL =-2.5 dB)			CASE B2 CL (6 Mbps) EL (27 Mbps)	CL (%25) / EL (% 75)		
	MCS	AWGN	INDUSTRIAL		MCS	AWGN	INDUSTRIAL
	BPSK 1/2	2.2	3.2		16-QAM 1/2	6.7	7.5
	16 QAM 1/2	11.1	11.9		16-QAM 3/4	10.6	11.6
CASE C CL (6 Mbps) EL (36 Mbps)	NOMA (IL =-4.0)			CASE C CL (6 Mbps) EL (36 Mbps)	CL (%33) / EL (% 66)		
	MCS	AWGN	INDUSTRIAL		MCS	AWGN	INDUSTRIAL
	BPSK 1/2	1.0	1.5		QPSK 3/4	4.1	5.3
	16 QAM 3/4	16.1	17.4		64-QAM 3/4	15.9	16.9
CASE D CL (6 Mbps) EL (48 Mbps)	NOMA (IL =-1,5dB)			CASE D CL (6 Mbps) EL (48 Mbps)	CL (%20) / EL (% 80)		
	MCS	AWGN	INDUSTRIAL		MCS	AWGN	INDUSTRIAL
	BPSK 1/2	3.30	3.8		16-QAM 3/4	10.6	11.6
	64QAM 2/3	18.1	19.2		64-QAM 5/6	17.6	18.8

Table 12: Theoretical threshold calculation for NOMA-based 802.11n

Table 12 describes five different use cases, which cover the most representative service configurations for the industrial environment. In all the cases, the CL has a minimum required throughput of 6 Mbps. This throughput is expected to guarantee the critical communications bitrate several clusters of sensors. Afterwards, five different enhance layer configurations aiming at covering different multimedia services ranging from 12 to 48 Mbps. In general, the MCS values for the TDM case has been selected in order to offer the capacity that is closer to the decided value. Even though, taking into account the numerology of the 802.11 family is it not possible to match perfectly those values.

Whereas the TDM based services thresholds are directly obtained from the values presented in [22], the NOMA based theoretical thresholds are calculated applying the formulas presented in [24]. In this case, the injection level for the NOMA cases has not been fixed and depending on the capacity that has to be achieve it has been selected. On the other side, the TDM shared resources are (50%-50%, 25%-75%, 33%-66% and 20%-80%).

The first important outcome is that the non-orthogonal solution is the only one capable of granting a SNR thresholds below 1 dB. Second, the TDM based require increasing the SNR value of the critical service up to 10.6 dB, providing the EL is close to 48 Mbps. Third, the more asymmetrical the services are the more noticeable the NOMA gain is. Nevertheless, it must be noted that when both services capacity requirement and SNR threshold is similar the NOMA gain is not so high. For instance, when the CL layer is offering 6 Mbps and the EL 12 Mbps, the TDM based solution (50%-50%) is also a good alternative.

Even though, as a general rule the asymmetry of services proposed NOMA based alternatives a very promising solution, and apparently, with better results than the ones obtained in Section 6.2.

6.3.2. PHY

First, the physical layer has been implemented for one and two layers, i.e., only the 802.11n standard and NOMA-based 802.11n.

6.3.2.1. Simulation setup

Similar to Section 6.2.2.1, in this Section, it is proposed to modify the 802.11n standard to include NOMA as a multiplexing solution, which can be understood as a low complexity NOMA case. Consequently, the architecture proposed in this document tries to minimize the complexity associated to a non-orthogonal receiver.

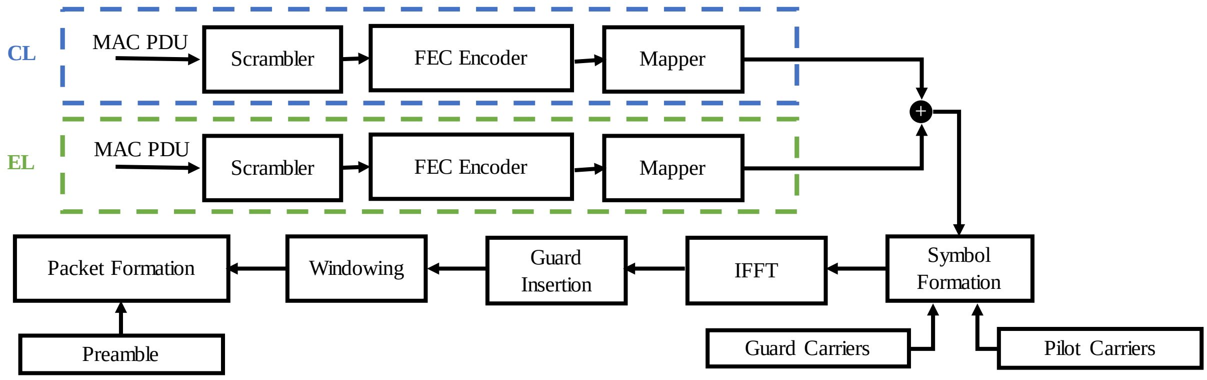


Figure 13: NOMA-based 802.11n transmitter

The transmitter side is composed of an adaptation module that prepares data for the error coding stage (see Figure 13). The mapping and framing stage are inherited directly from 802.11n Modulation and Coding Schemes (MCS). The only difference is that after mapping, both services are combined into a single stream. The next stages are equivalent for both services as they are one ensemble. The final physical waveform are PHY packets composed of a preamble and a data field. The detailed structure of the PHY packet is maintained as defined in 802.11n. However, there is one additional requirement: the packet length of the enhance layer service is selected in order to match the same number of symbol per frame that the core layer service. It must be taken into account that the maximum length of the PSDU is 4095 bytes.

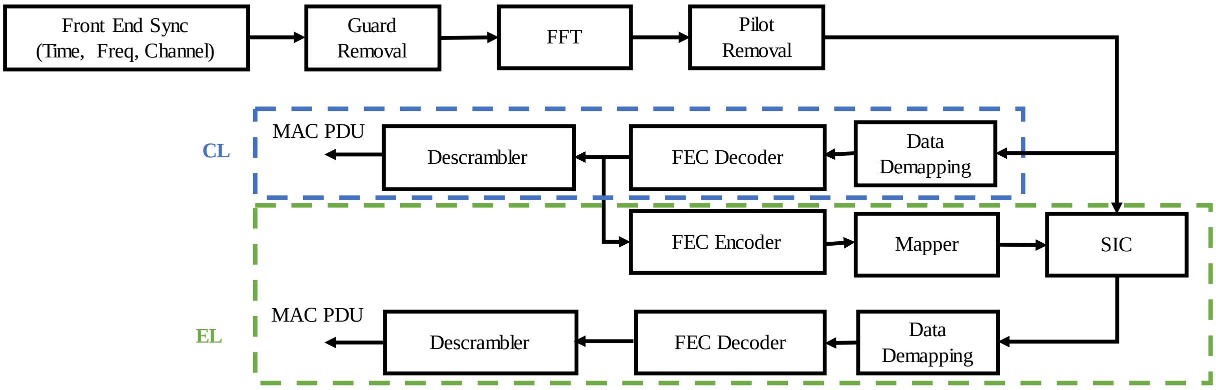


Figure 14: NOMA-based 802.11n receiver

Due to the proposed transmitter structure, the first modules of the NOMA receiver are identical to existing 802.11n receivers. After RF conditioning, the carrier and time synch stages prepare the input for channel and equivalent noise estimation, operation performed based on the information conveyed in HT-LTF and HT-SIG sections. The HT-SIG also helps in detecting the MCS choices of the received PHY packet. All these information pieces aid on OFDM symbol recovery and subcarrier.

After equalization, the CL decoding is carried out by decoding, demapping and descrambling modules. This CL bit stream will be available for all sensor/actuators in the service area. If the available SNR permits, the cancellation and enhance layer decoding will be the next steps. The cancellation will depend on the injection level value, the channel estimation metrics and the CL itself. Once the CL has been cancelled the EL decoding, demapping and interleaving are straightforward. At the receiver, the NOMA ensemble on the *k*-th channel can be expressed can be expressed as,

$$y_{NOMA}(k) = \left(x_{CL}(k) + g \cdot x_{EL}(k)\right) \cdot h(k) + n(k) \qquad (4)$$

Where $y_{NOMA}(k)$ is the received symbol, *h* (*k*) is a static multipath channel and *n* (*k*) is the sum of AWGN noise and other additive interference. Equalization is a key step in CL decoding and subsequent cancellation.

Once the CL has been decoded, a signal cancellation algorithm must be implemented in order to access to the EL. In this work, it is proposed to use the H-SIC cancellation scheme, because it offers a very good trade-off between complexity and performance. The decoded CL is coded and modulated again, and then, it is removed from the equalized NOMA signal. Afterwards, the received can be expressed as:

$$x_{S2}(k) = g \cdot x_{EL}(k) + i(k) + n(k) \qquad (5)$$

where i(*k)* is the error cancellation due to the channel estimation error.

In order to do so, a complete transmitter and receiver chain fully compliant with the 802.11n standard has been implemented. Afterwards, several modifications have been introduced in the transceiver chain in order to make it possible to multiplex services in NOM basis.

First, at the MAC layer the two different layers PSDU packet length is theoretically adjusted in order to assure that they will require the same numbers of symbols per frame. Consequently, after the mapping block a NOMA simplified approach could be used, and thus, the receiver architecture will be simplified. In general, the EL PSDU length should be calculated as:

$$PSDU_{EL} = \lfloor (Sym_{Num} * NDBPS_{EL} - N_{Service})/8 \rfloor \quad (6)$$

Afterwards, the transmitter block has been updated according to Figure 13 to combine by power multiplexing two different services. The two layers are added after the mapping block according to the selected injection level.

Following the methodology already applied to the case of the 802.11g standard, both the AWGN and a static industrial channel model with Non-Line-Of-Sight (NLOS) and 29 ns rms delay [25] are implemented.

The performance is evaluated through BER and PER. In particular, for each SNR value more than 2000 packets are tested, depending on the configurations. A PSDU packet is considered erroneous is any of the bits are decoded incorrectly. Finally, it must be noted that the simulation step is 0.1 dB.

6.3.2.2. Results

First, the single layer simulations are studied for testing the performance of the single service, which afterwards will be used as a reference for the TDM vs NOMA comparison.

The results are gathered in Figure 15. Actually, 802.11n thresholds for the different MCS values for both the AWGN and INDUSTRIAL channel models are plotted in the figure. In addition, the Shannon-Harthley ideal capacity has been included in order to validate the performance of the implemented LDPC codes. The SNR values are obtained for a BER value of 10^{-2}.

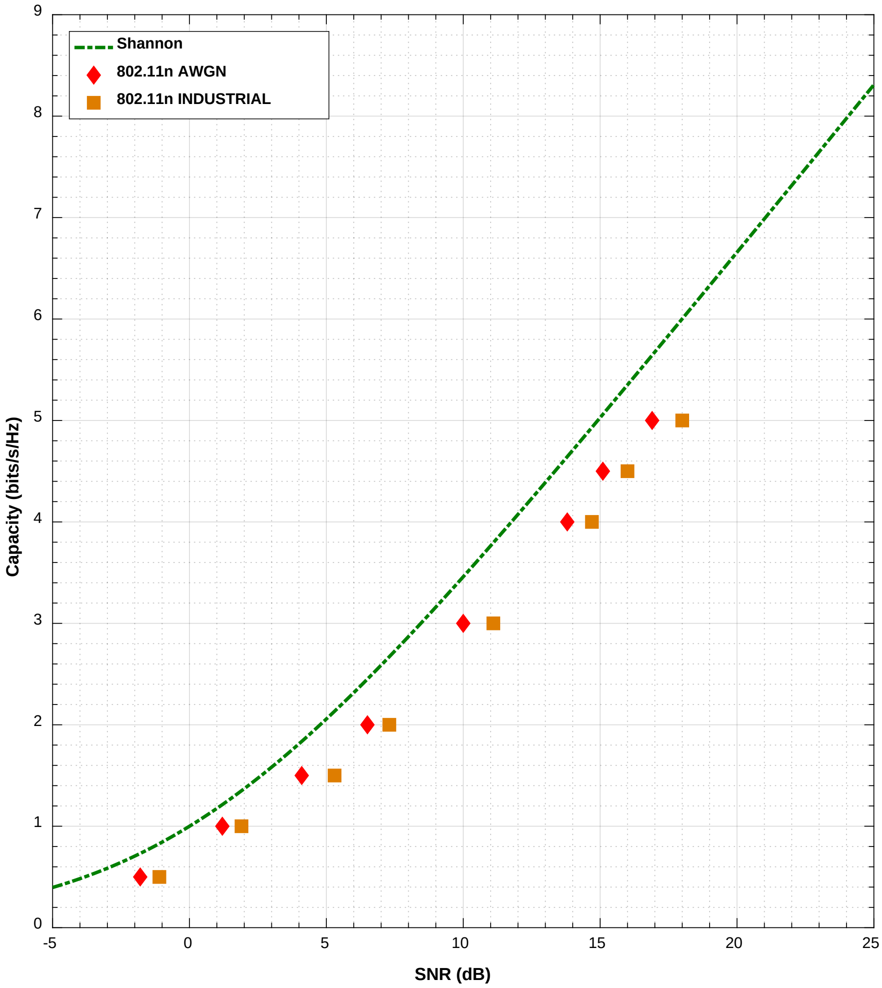


Figure 15: 802.11n one layer thresholds for PER 10^{-2}

In general, the graphic shows that the distance from Shannon for the AWGN case is between 1 and 2 dB depending on the MCS selection. Therefore, it can be assumed that the FEC efficiency is enough to maintain the NOMA gain versus the orthogonal methods [20].

What is more, it can be also seen that for a multipath environment (the industrial channel) the difference with respect to the AWGN channel ranges from 0.5 to 1 dB, and consequently, the proposed 802.11n can be implemented in an industrial environments.

Once the platform has been validated, the next step is to test the NOMA proposal and compare the results with the traditional TDM/FDM schemes. The SNR vs. PER curves for each of the presented cases in Table 12 are painted in Figure 16 and Figure 17, differentiating CL and EL of each case, respectively.

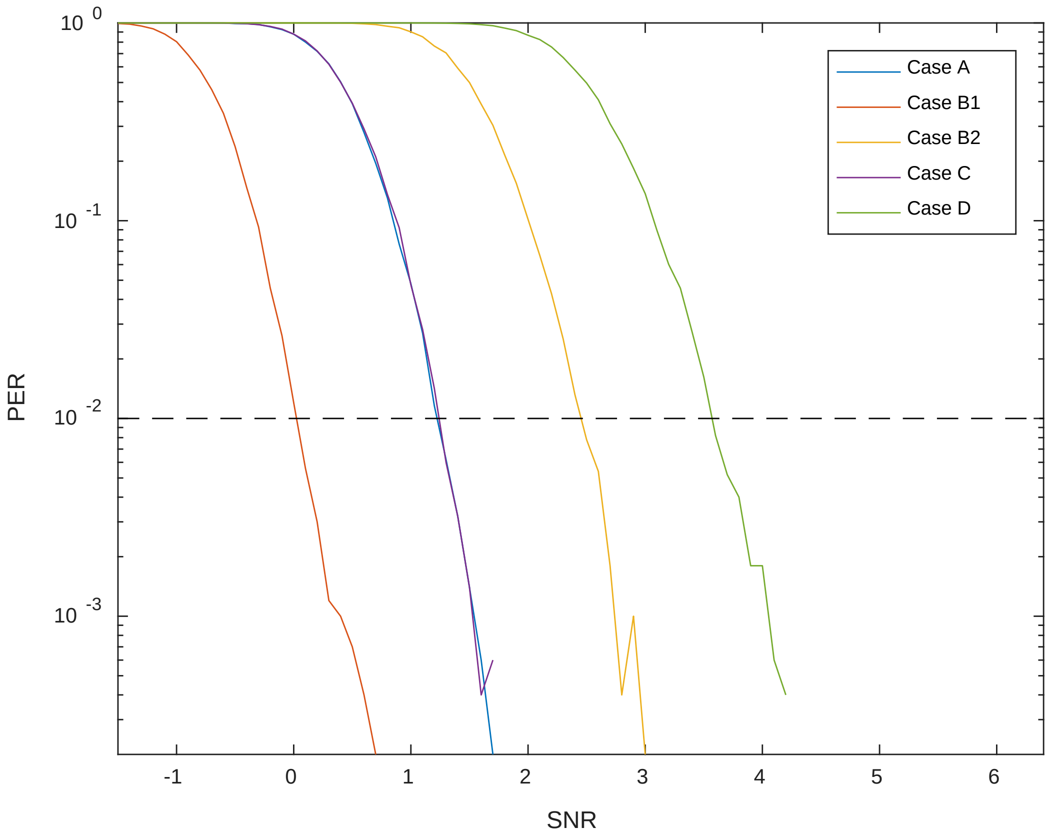


Figure 16: NOMA-based 802.11n CL thresholds

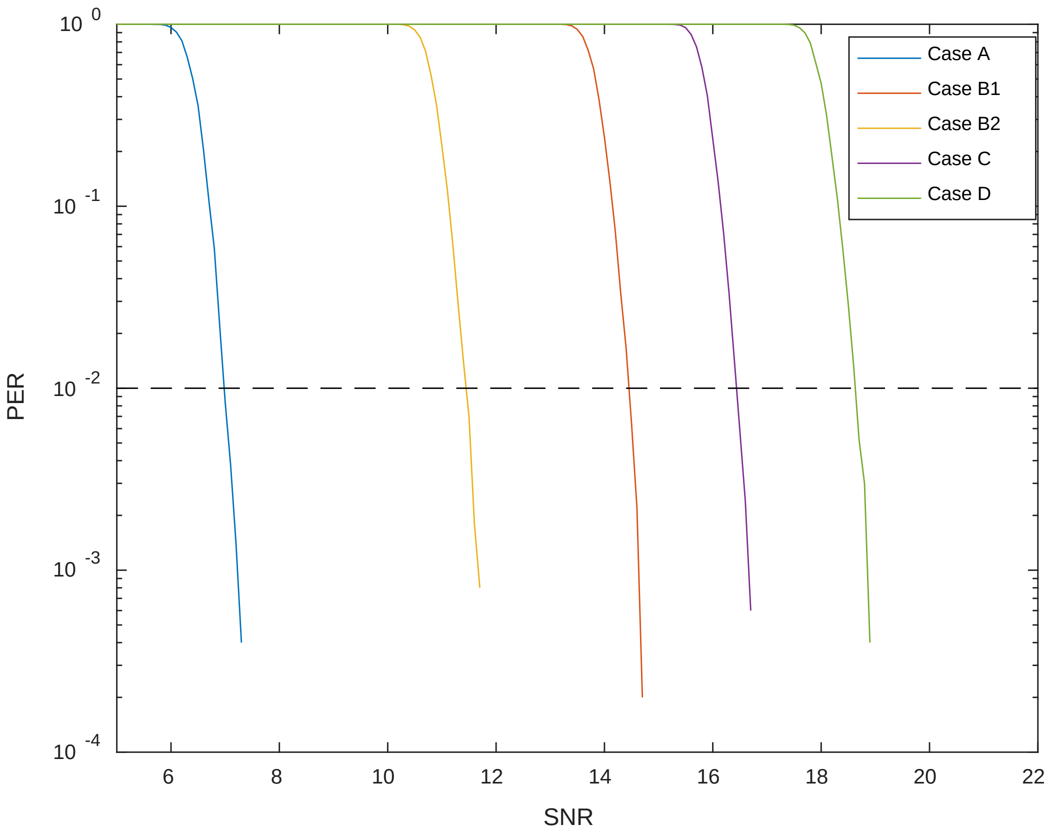
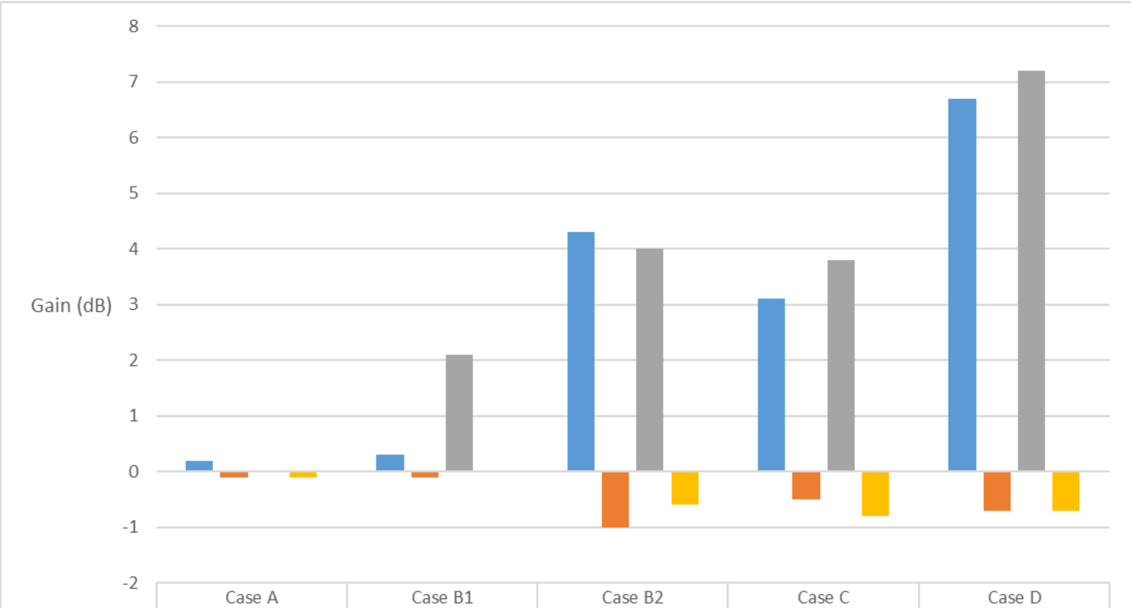


Figure 17: NOMA-based 802.11n EL thresholds

The difference in the NOMA simulations between the predicted value and the simulated value ranges from 0.1 to 0.3 dB. This difference between predictions and simulations, negligible for validation purposes, is due to packet length differences required for simulating two synchronized layers.

The CL performance gain is 0.2, 0.3, 4.3, 3.1 and 6.7 dB for each of the cases, where the EL loss is 0.1, 0.1, 1,0.5 and 0.7 dB for the AWGN case. For the industrial channel model, the gain is 0, 2.1, 4, 3.8 and 7.2 dB for each case, where the loss for the EL is 0.1, 0, 0.6, 0.8 and 0.7 dB. These results are gathered in Figure 18.



	Case A	Case B1	Case B2	Case C	Case D
AWGN - CL	0.2	0.3	4.3	3.1	6.7
AWGN - EL	-0.1	-0.1	-1	-0.5	-0.7
IND - CL	0	2.1	4	3.8	7.2
IND - EL	-0.1	0	-0.6	-0.8	-0.7

Figure 18: PHY gain summary

In short, the NOMA approach show a remarkable SNR gain, which increases with the capacity inequality among layers. The bigger the data throughput asymmetry the bigger the NOMA gain. Eventually, it is also important to note that the proposed SNR thresholds are always smaller than 20 dB.

6.3.3. MAC

Once PHY layer is completely validated, the capacity of the MAC layer has been evaluated using the results of the physical layer simulations.

6.3.3.1. Simulation methodology

The methodology applied for the simulation of the MAC level of this proposal is the same as the one used in Section 6.2.3.1. The main difference are the PER vs SNR curves used, since in this case the ones obtained from simulating Section 6.3.2 are used.

6.3.3.2. Use case

For the use case, a similar scenario as the one used in Section 6.2.3.2 has been considered.

The same network as for the NOMA-based 802.11g has been assumed, that is, a central node (Access Point, AP) located in the center of the facility and 20 slave nodes distributed randomly. Devices usually related to the industry in IWSN networks, as sensors or actuators, are represented by slaves where in this case they are traffic receivers and transmitters. However, the AP is the master node of both the architecture and the synchronization, and distributes information to all the devices connected in the network. The transmitted type of traffic is maintained equal by implementing RT and BE with the same requirements and characteristics. Finally, the time schedules followed by each technology are the same as the ones presented in Figure 11 and Figure 12, for TDMA and NOMA, respectively.

One of the main differences is the transmitted packet size, since a reduction in the cycle time is needed to fulfil the requirements established in Section 5.1 for FA and PA environments communications. In order to make a fair comparison between both technologies, the amount of information sent must be established. For this, the time taken to transmit the amount of information of an LDPC block with the lowest MCS (BPSK 1/2) has been taken as reference, 180 µs. During this time slot, using NOMA, both the RT and BE services are transmitted. However, for TDMA-based cases, the 180 µs are shared between RT traffic and BE traffic depending on the time distribution used (Table 12). In this way, the information transmitted in relation to each type of traffic is the same for both multiplexing mechanisms, with the time distribution and injection level being the parameters that define the amount of data of each service. Hence, a complete cycle time has always fix duration, which is equal to 40 NOMA time slots (Figure 12), 7.2 ms. Due to that cycle time length, the update time requirements that are established for industrial communications and detailed in Section 5.1 are met. Table 13 shows the composition of the cycle time of each of the proposed study cases.

According to each type of traffic requirements, a specific data rate has been assigned. In the case of RT traffic, a requirement of 6 Mbps has been assumed, and for the BE traffic different possible scenarios has been taken into account, 12, 24, 36, 48 Mbps requirements (Table 12). Because of the temporary distribution made in TDMA, to offer the same capacity as NOMA for a service, higher MCS should be used, assuming an important penalty in reliability. In Table 13, a summary of the cases that have been simulated for both TDMA and NOMA is shown.

Case	MCS	RT segment (ms)	BE segment (ms)	Tcycle (ms)
A – NOMA	0 & 1	7.2	7.2	7.2
A – TDMA	1 & 3	3.6	3.6	7.2
B1 – NOMA	0 & 3	7.2	7.2	7.2
B1 – TDMA	1 & 5	3.6	3.6	7.2
B2 – NOMA	0 & 3	7.2	7.2	7.2
B2 – TDMA	3 & 4	1.8	5.4	7.2
C – NOMA	0 & 4	7.2	7.2	7.2
C – TDMA	2 & 6	2.4	4.8	7.2
D – NOMA	0 & 5	7.2	7.2	7.2
D - TDMA	4 & 7	1.44	5.76	7.2

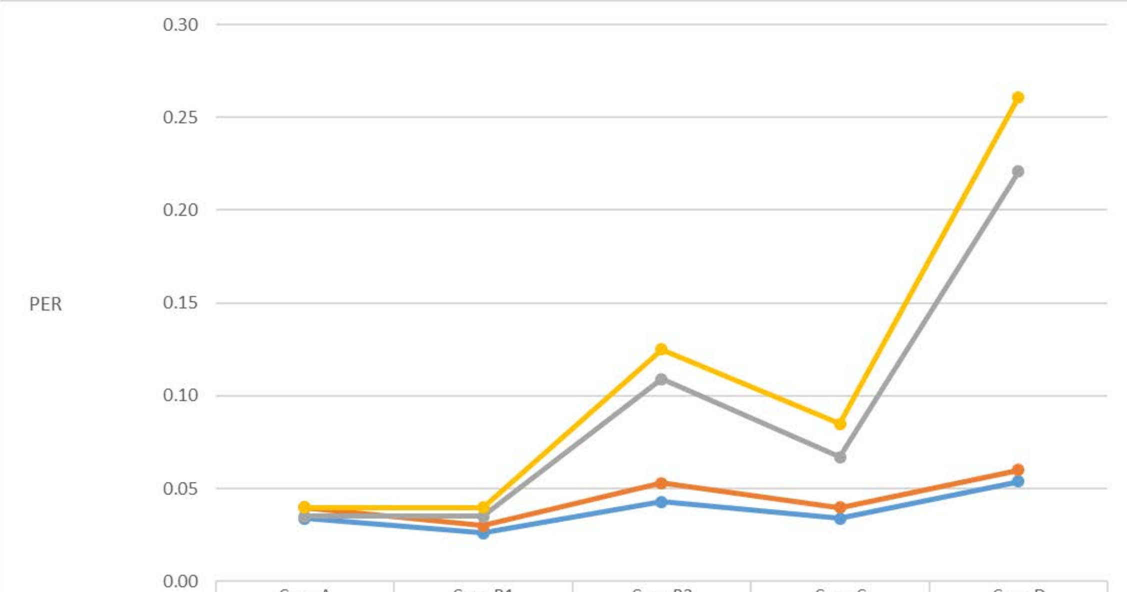
Table 13: MAC level simulation configurations

In this case, as well, in order to obtain as much realistic results as possible, twenty simulations have been carried out with each configuration, varying the seed in each of them to obtain different distributions of the equipment. Each of the nodes transmits 10 dBm. The simulated area is 100x100 meters long, a Rayleigh channel is assumed and the path loss exponent is set to 2.5 to fix with industrial indoor communications [26].

6.3.3.3. Results

Once the use case used to validate the proposal is presented, the results are shown in Figure 19 and in Figure 20, for RT and BE traffic, respectively.

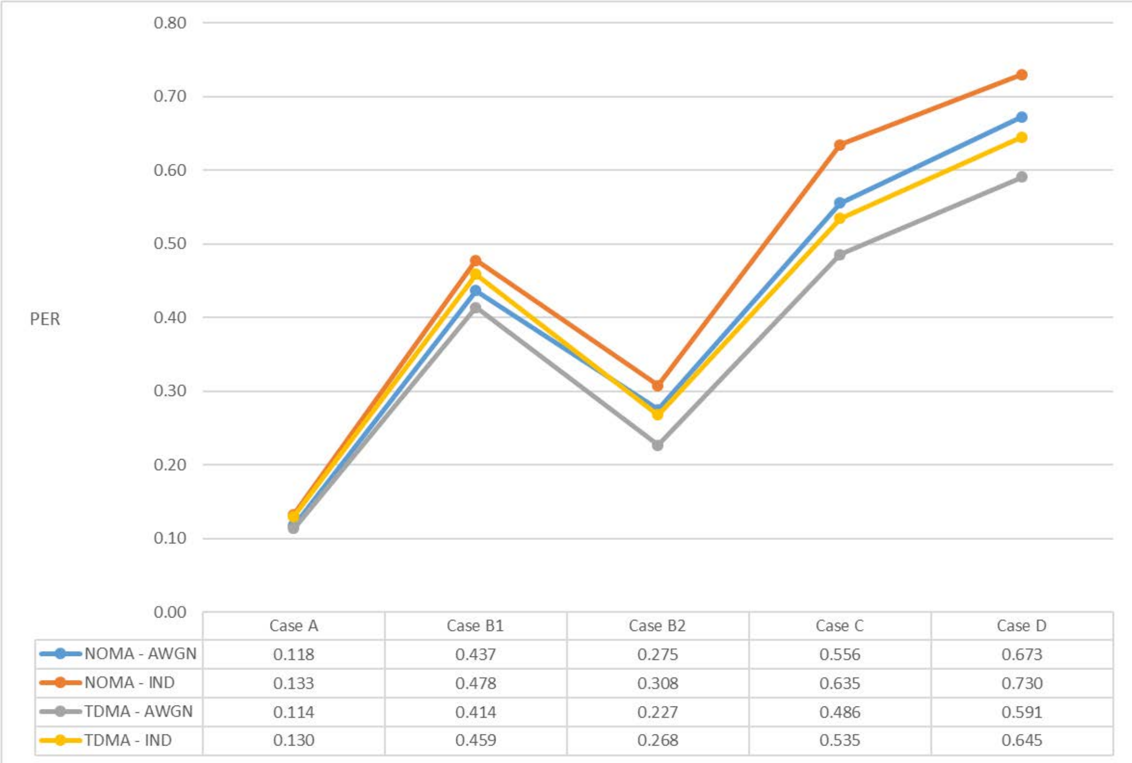
First, for the AWGN channel simulations, it should be noted that NOMA based RT services are more robust than TDMA based ones. In fact, NOMA-based architectures obtain for each case a PER below 10^{-1}, since in some cases those values are closer to 10^{-2}. In addition, although different cases are evaluated, NOMA always offers a similar reliability performance. However, in TDMA-based architectures it be always obtained a PER lower than 10^{-1} and the success rate obtained in the last three cases is not enough to guarantee the correct transmission of the RT service. It is important to highlight that in TDMA-based simulations, there is not a constant trend on the obtained PER as it happens in NOMA, and so, there are only available the first two cases, while using NOMA, each of the cases could be implemented. Definitely, this implies a considerable increase in the reliability of the communication. However, for BE services results trend is opposite. In this case, NOMA-based services have a higher error rate, although this traffic type characteristics are not as strict as RT traffic ones, so that success different is assumable.



	Case A	Case B1	Case B2	Case C	Case D
NOMA - AWGN	0.034	0.026	0.043	0.034	0.054
NOMA - IND	0.040	0.030	0.053	0.040	0.060
TDMA - AWGN	0.035	0.035	0.109	0.067	0.221
TDMA - IND	0.040	0.040	0.125	0.085	0.261

Figure 19: MAC level PER for RT traffic

Secondly, in the industrial channel case, it can be seen that although the results generally contain a greater number of losses, the trend remains because the threshold requirements are higher. That is, the NOMA-based systems offer a significant increase in the robustness of the RT services and a higher loss rate in the BE services. Moreover, for NOMA-based cases, a PER lower than 10^{-1} is always achieved while for TDMA-based cases, again, only twice is achieved and the last three cases are not possible due to the high loss rate in the critical service.



	Case A	Case B1	Case B2	Case C	Case D
NOMA - AWGN	0.118	0.437	0.275	0.556	0.673
NOMA - IND	0.133	0.478	0.308	0.635	0.730
TDMA - AWGN	0.114	0.414	0.227	0.486	0.591
TDMA - IND	0.130	0.459	0.268	0.535	0.645

Figure 20: MAC level PER for BE traffic

As already discussed in Section 6.2.3.3, it is important to highlight the role played by each of the services and their requirements. The robustness increase the of the RT services is critical; for instance, if synchronization information is send by RT services, a failure in the transmission can result in the loss of an entire superframe, that is, that the packet losses in the information of synchronization directly affect BE traffic and other RT traffic.

It should be noted that in this first step of this new technology integration, retransmissions are not included. That is why, PER values are not as low as the ones mentioned in Section 5.1. However, implementing retransmissions in this NOMA-based communication system is an interest topic, and taking as a reference works that apply for a similar environments, as [7], depending on the redundancy level of the retransmissions, a MAC level PER of 10^{-8} is affordable for the PHY level PER values presented in Section 6.3.2.2

Following the same line as in Section 6.2.3.3 due to the temporary reorganization of the services, a considerable gain in determinism has been obtained for BE services. Using NOMA techniques, as BE services are transmitted in the lower layer and they are aligned with RT services, which need high reliability, it is much easier to determine the timing of the transmission and the reception of each BE package, and therefore, it is easier to predict their latency, among other parameters.

7. Task Description

The phases in which the project is composed, the tasks that make up each of them, and their duration in weeks are described below. The information is shown from Table 14 to Table 20.

7.1. Task Definition

7.1.1. Work Package 1

WP1: Project management	Duration (weeks)
T1.1: Project management and coordination	55.5

Table 14: Work Package 1 description

T1.1: This task has the same duration as the whole project (33 weeks) because it contains all the aspects related to its planning. It includes the definition of the objectives, the monitoring and control of the development and the identification of risks together with its contingency plan.

7.1.2. Work Package 2

WP2: Previous analysis	Duration (weeks)
T2.1: Analysis of the state of art of the industrial communications	5
T2.2: Creation of database of industrial use cases	5
M1: Database presentation	-

Table 15: Work Package 2 description

T2.1: This task includes the search and reading of the information needed to know the NOMA technology, industrial communications, LDPC codes and IEEE 802.11g standard.

T2.2: This task consists in compiling in a database the basic information of the most relevant documentation read to know the state of the art of the topics mentioned in task T2.1. The database focuses on recognizing applications, sectors or industrial use cases, and distinguishing the requirements and the solutions applied.

M1: Bibliographic data presentation and discussion.

7.1.3. Work Package 3

WP3: NOMA over package simulator (OMNeT++)	Duration (weeks)
T3.1: Learning tutorial	4
T3.2: Real network emulation	3
T3.3: NOMA over OMNeT++	5
M2: Presentation of the demonstrator	-
M3: NOMA test run	-

Table 16: Work Package 3 description

T3.1: Because the student had not worked with package simulators, this task serves as a familiarization with the OMNeT++ tool. For this, an OMNeT++ tutorial is carried out in which is learned to manage the tool for the different layers of the protocol stack and to manage the characteristics of the simulation scenario.

T3.2: In order to put into practice the tutorial carried out in the previous task, a practical task is done. For this purpose, a hybrid demonstrator (wired and wireless network) based on 6 nodes used in Ikerlan has been taken as a reference and emulated by OMNeT++. For this, a MAC layer based on TDMA has been implemented, together with the intercommunication between the nodes.

T3.3: Once the OMNeT++ performance has been understood, NOMA has been implemented on it. For this, it has started with a transmitter/receiver system of the 802.11g/n standard and it has been modified to adapt it to the requirements of the NOMA technology.

M2: Presentation and checking of the developed demonstrator.

M3: Presentation of several test run in order to validate the developed NOMA model over OMNeT++.

7.1.4. Work Package 4

WP4: PHY level design	Duration (weeks)
T4.1: Study of an 802.11g/n example code	3
T4.2: Study of an NOMA example code	3
T4.3: Development of an 802.11g/n receiver/transmitter system	5
T4.4: Development of an 802.11g/n + NOMA receiver/transmitter system	5
M4: 802.11g/n PER/SNR curves	-
M5: 802.11g/n + NOMA PER/SNR curves	-

Table 17: Work Package 4 description

T4.1: This task consists of analyzing and knowing the basic structure of a Matlab code that implements a data transmission/reception system based on the IEEE 802.11g/n standard. It is the most basic system, so it is important to understand it in order to adapt it to the system proposed in this project.

T4.2: This task consists of analyzing, understanding and knowing how to handle the functions and the code that allows the implementation of an NOMA system through Matlab. As with the previous task, since it is the basis for developing the proposed project, it is important to understand the code well.

T4.3: The aim of this task is to develop a system for transmitting/receiving data packets through the use of the IEEE 802.11g/n standard. The correct development of the system is essential since the results obtained are directly used in WP5 and the code is reused in the next task.

T4.4: This task consists of developing the Matlab the code that implements the system proposed in this project. First, the code developed in task T4.2 must be adapted. On the other hand, the code of the IEEE 802.11g system developed in task T4.3 must be modified to adapt it to the requirements of the proposed system. Finally, the complete system is developed from the combination of the two previous codes.

M4: Obtainment and presentation of the PER/SNR curves of the developed 802.11g/n transmitting/receiving model.

M5: Obtainment and presentation of the PER/SNR curves of the developed overall transmitting/receiving system model.

7.1.5. Work Package 5

WP5: Industrial use case	Duration (weeks)
T5.1: Use case design	2
T5.2: Use case and MAC level codification	4
M6: Use case requirements/characteristics document	-

Table 18: Work Package 5 description

T5.1: Before starting the MAC level evaluation in OMNeT++, it is necessary to establish the use case that is going to be simulated. In this task, taking into account the database developed in task T2.2, the evaluating use case is defined: number of nodes, temporary requirements, time scheduler…

T5.2: In this task the use case defined in the previous task is codified and the TDMA based MAC protocol as well.

M6: Defined use case characteristics and requirements summary document.

7.1.6. Work Package 6

WP6: Results analysis	Duration (weeks)
T6.1: MAC and PHY level results obtaining	4
T6.2: Conclusions	2
M7: Results comparison	-

Table 19: Work Package 6 description

T6.1: In order to obtain MAC and PHY level results, a dual simulation has to be carried out. Firstly, the PHY results are obtained by using the Matlab system model. And, secondly, using as input those results, MAC results are obtained from the OMNeT++ system model.

T6.2: This task consists in comparing the results obtained and in drawing conclusions about them. In this way it is possible to determine if the proposed system offers improvements with respect to the original unmodified system.

M7: Obtained results are presented in a comparative way.

7.1.7. Work Package 7

WP7: Documentation	Duration (weeks)
T7.1: Document writting	5.5
M8: Final document	-

Table 20: Work Package 7 description

T7.1: This task is carried out at the end of the project, and in it the report is written, which includes the methodology used, the results and conclusions, among others.

M8: Presentation of final documentation.

7.2. Gantt Diagram

The Gantt diagram is presented below by means of Figure XX. This representation allows to visually know what are the relationships between the tasks and work packages as well as their durations and the milestones established during the development of the project.

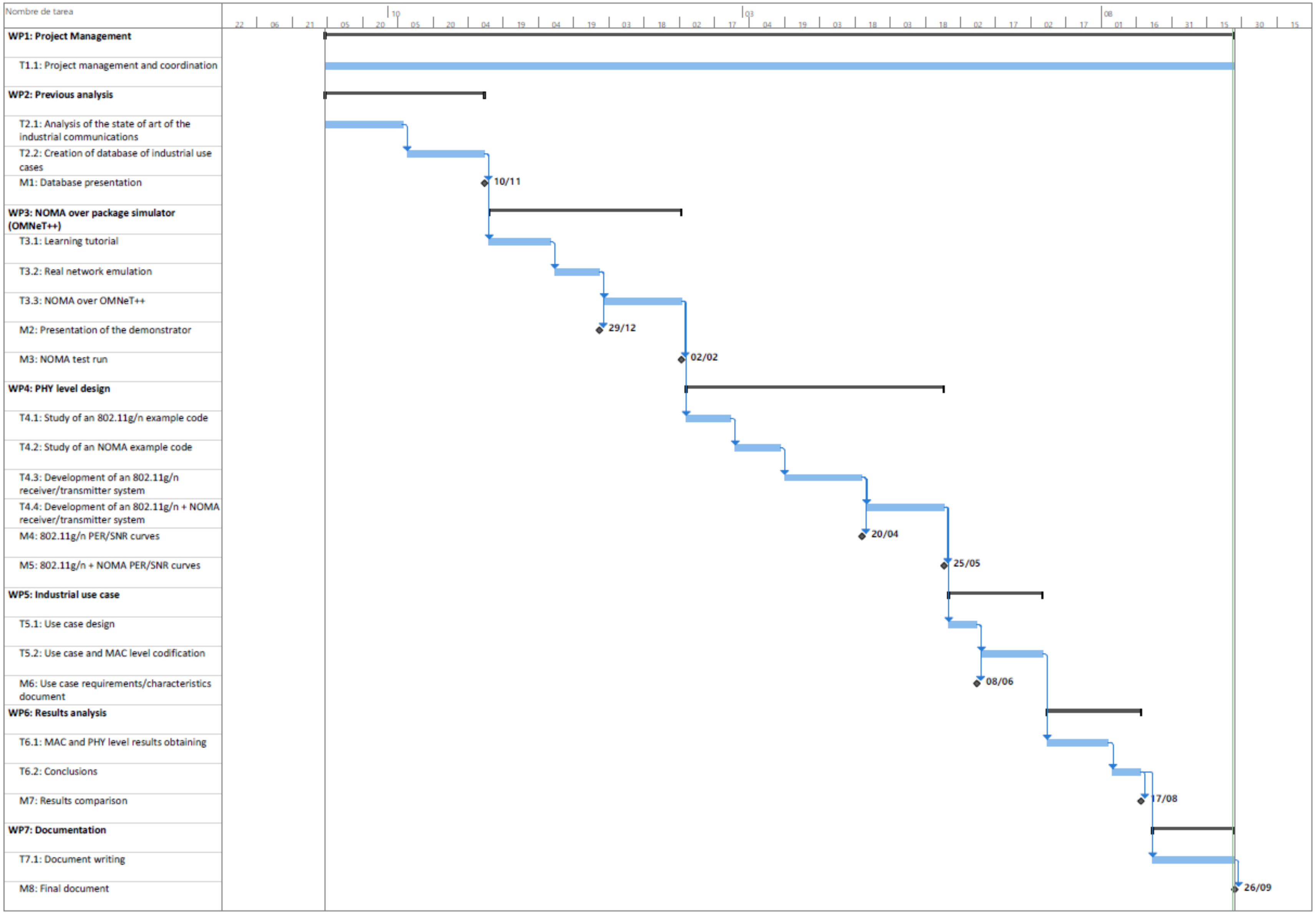


Figure 21: Gantt diagram

8. Expense Summary

In this section the expenses summary of the project is presented. It consists on the internal hours, amortizations, expenses, subcontracting and indirect costs, broken down below by the following sections.

8.1. Internal hours

The expense produced by the internal hours, that is, the hourly cost of each member participating in the present project is shown in Table 21.

Researcher	Position	Category	Hourly rate (€/h)	Hours	Total (€)
Pablo Angueira	Director	Senior engineer	80	50	4000
Jon Montalban	Researcher	Senior engineer	80	200	16000
Iñaki Val	Co-director	Senior engineer	80	50	4000
Eneko Iradier	Project executor	Junior engineer	30	800	24000
		Subtotal			48000

Table 21: Internal hours

8.2. Amortizations

Table 22 shows all those elements that have been used to carry out this project and that can be used in future projects.

Concept	Initial Cost (€)	Useful Life	Used Time	Total (€)
Computer	1000	5 years	9 month	150
Windows 7 OS	200	One year	9 month	150
Microsoft Office 2007	150	One year	6 month	75
Matlab License	1500	One year	3 month	375
		Subtotal		750

Table 22: Amortizations

8.3. Expenses

Expenses are considered all those materials used in the project that, once used, can no longer be used, such as office material.

The total cost of this section is € 50.00.

8.4. Subcontracting

Subcontracts refer to contracts made to third parties for the realization of any of the tasks of the project. In this case, no type of subcontracting has been required, so the total expense of this budget item is € 0.00.

8.5. Indirect costs

Indirect costs are considered those that are not imputable in any project such as water, electricity, cleaning, etc. They are calculated as a percentage of direct expenses, which are all the previous ones.

In this case, a value of 2% is assigned with respect to direct costs.

8.6. Summary

Below is presented in Table 23 the summary of the total budget in which each of the items previously analyzed is included.

Concept	Amount (€)
Internal hours	48000.00
Amortizations	750.00
Expenses	50.00
Subcontracting	0.00
Subtotal	48800.00
Indirect costs (2%)	976.00
Total	49776.00

Table 23: Expense summary

9. Risk Analysis

During the execution of any project there are a number of risks, which may affect the development and the results. Therefore, in this section the risks that may appear will be analyzed. To do this, first each of these risks will be identified, explaining the reason for its appearance and its consequences. After that, the established contingency plan will be proposed to face each of the risks in case of appearing. Finally, the risks will be classified through a matrix in which the probability of occurrence and impact are quantified.

9.1. Risk definition

A list of the risks that have been identified, as well as the contingency plan assigned to each of them is listed below.

Non-representative scenarios (R1)

Taking into account that the proposal is focused on a specific sector, one of the existing risks is that the scenarios proposed for the validation of the system are not representative in the current industrial environment. That is, that the set of selected parameters does not reflect a real industrial environment, and therefore, simulations are not applicable.

To avoid this risk, a study has been carried out before the elaboration of the proposal in which it has been investigated about the use cases and the existing applications. Through this task, the possible values to be assigned to each of the parameters that make up the scenario are delimited.

Not meeting industrial communications requirements (R2)

Similar to R1 risk, it would be possible that once the proposal is developed and tested, the requirements of basic needs of industrial communications, such as robustness, latency or cycle times, would not be met. As in R1 risk, the consequence of this risk would be the lack of applicability in the industrial field.

This risk, if it occurs, is difficult to avoid, but it is possible to reduce its impact. Therefore, prior to the design of the PHY, a theoretical analysis will be carried out to guarantee representative and useful SNR threshold values. Besides that, at MAC level, the time schedules will be designed according to the literature in order to comply with the necessary latency and cycle times.

Low performance due to convolutional codes (R3)

The convolutional codes are a point to take into account in this project, since their performance is not efficient and can be a problem for integration with NOMA systems. As has been proven in the literature, being too far from the theoretical Shannon limit is more harmful to the NOMA system than to TDM systems, and this type of codes can lead to these differences with respect to the theoretical maximum value.

Avoiding this risk is difficult, since it is something completely out of the control of this project. In any case, it is easily predictable. Once the design of the PHY is done, when comparing the results obtained with both technologies, it will be possible to see how far each technology with respect to the Shannon limit is. Then, firstly, the configurations that enhance the qualities of the NOMA systems with respect to TDM will be designed. And secondly, and if the first option is not enough, the use of codes that provide greater efficiency in future work will be planned, such as the LDPC, already used in the IEEE 802.11n standard.

9.2. Risk evaluation

As mentioned, each of the risks identified in the previous section will be weighed based on the impact and the probability of occurrence that they have from zero to one. That weighting is shown in Table 24, where it is necessary to be especially careful with the risks located in orange and red colors, since they are the most dangerous for the project.

Probability	Impact				
	Very low (0.1)	**Low (0.3)**	**Medium (0.5)**	**High (0.7)**	**Very high (0.9)**
Very low (0.1)			R1		
Low (0.3)				R2	
Medium (0.5)				R3	
High (0.7)					
Very high (0.9)					

Table 24: Risk matrix

As shown in the table above, special care with risks R2 and R3 must be taken, especially with the last one, since their probability and impact combination is remarkably representative. For this reason, the contingency plans will be prepared just in case their imminent start-up is necessary.

10. Conclusions

During this project, NOMA technologies are presented as an alternative of the actual PHY layer of the well-known IEEE 802.11 standard family. Through the project, the benefits of modifying the 802.11 standard have been underlined. In this section, the main technical conclusions are presented.

Firstly, in the case of NOMA-based 802.11g implementation, it has been observed that NOMA offers better results of the robustness for the RT services and a higher flexibility of the possible offer of services. There are MCS combinations that cannot be used with TDMA. In spite of this, it is true that in some cases TDMA based systems offer slightly better results in some aspects, especially for BE services. As already mentioned, this is mainly due to two factors. First, that the numerology of the 802.11g standard modes is critical in the offer of NOMA, since few modes are offered and they are not unbalanced enough to obtain maximum efficiency. Second, the use of convolutional codes in the 802.11g standard causes to be very far away from Shannon's theoretical ideal limit, which handicaps the NOMA techniques.

On the case of NOMA-based 802.11n architecture results, NOMA offers a considerable gain in the robustness of the RT services, and a quite constant success index, in comparison with TDMA. The flexibility in the characteristics of the services offered is again increased. However, the BE service results behavior is similar to the one obtained for the 802.11g standard development. As already mentioned, this is mainly due to the numerology of the 802.11n standard modes, since few modes are offered and they are not unbalanced enough to maximize efficiency.

In all proposed scenarios, the reliability of RT services has been improved significantly using NOMA. In fact, losses are reduced around an order of magnitude. It is also essential to emphasize that the concept of robustness is critical to RT services, since an error in the RT packages can cause errors in the rest of the super frame, involving not only BE traffic, but also RT traffic.

In addition, the proposal in this project provides an extra advantage with respect to TDMA: determinism in BE services. Using the MAC structure described in this proposal, the latency becomes predictable in industrial communications.

Definitely, this work is the beginning of a probably new research line, and so, there are many open questions to investigate. First, some typical mechanisms for reliability increase could be combined with NOMA schemes, for instance, retransmissions. The introduction of this mechanisms would lead to an interesting compromise between the increase of reliability and the increase of the communication latency.

From a PHY perspective, even though an industrial channel has been implemented for the threshold calculation, mobility has not been taken into account. Hence, another interesting point is the effect of Doppler based channel in this kind of communications, and, specially, find the best way to reduce its impact on the results.

Looking for an increase in realism it would be interesting to validate this proposal in an industrial environment with real hardware. Hence, how to implement this proposal in commercial devices would be studied and creating compatible transceivers with NOMA technology.

In a more generic way, today's MAC solutions require improvement in order to adapt them to NOMA architectures. Depending on the MAC layer type, the best evaluation metric could be different and in consequence a matter of research.

Related to network planning and deployment, a new research work could focus in the energy consumption. In this work, the main focused of interest has been put in reliability, whereas in wireless industrial networks, energy consumption is as well a critical parameter. A promising field in this area is the sought of MAC layer algorithms that offer a gain in terms of consumption based on NOMA characteristics.

Finally, and similar to energy consumption, latency needs its own mention. This parameter is critical in order to fulfill cycle times and not to delay critical information delivery. Hence, MAC layer algorithms are going to be investigated to reduce latency in this kind of applications taking always into account the characteristics of NOMA.

11. Bibliography

[1] A. Varghese y D. Tandur, «Wireless requirements and challenges in Industry 4.0,» de International Conference on Contemporary Computing and Informatics (IC3I), Mysore, India, 2014.

[2] P. Suriyachai, U. Roedig y A. Scott, «A Survey of MAC Protocols for Mission-Critical Applications in Wireless Sensor Networks,» IEEE Communications Surveys & Tutorials, vol. 14, nº 2, pp. 240-264, 2012.

[3] V. Díez, A. Arriola, I. Val y M. Vélez, «Validation of RF Communication Systems for Industry 4.0 through Channel Modeling and Emulation,» de *IEEE International Workshop of Electronics, Control, Measurement, Signals and their application to Mechatronics*, Donostia-San Sebastián, España, 2017.

[4] A. A. Kumar S., K. Ovsthus y L. M. Kristensen, «An Industrial Perspective on Wireless Sensor Networks - A Survey of Requirements, Protocols, and Challenges,» IEEE Communcations Surveys & Tutorials, vol. 16, nº 3, pp. 1391-1412, 2014.

[5] IEEE, «Orthogonal frequency division multiplexing (OFDM) PHY specification,» de 802.11 Standard - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Nueva York, Estados Unidos, IEEE Computer Society, 2012, pp. 1583-1630.

[6] Fernandez, Z., Cruces, C., Val, I., & Mendicute, M. (2017, May). Deterministic real-time access point concepts for industrial hybrid Ethernet/IEEE 802.11 networks. In Electronics, Control, Measurement, Signals and their Application to Mechatronics (ECMSM), 2017 IEEE International Workshop of (pp. 1-6). IEEE

[7] Luvisotto, M., Pang, Z., & Dzung, D. (2017). Ultra high performance wireless control for critical applications: Challenges and directions. IEEE Transactions on Industrial Informatics, 13(3), 1448-1459

[8] Seijo, Ó., Fernández, Z., Val, I., & López-Fernández, J. A. (2018, June). SHARP: A novel hybrid architecture for industrial wireless sensor and actuator networks. In 2018 14th IEEE International Workshop on Factory Communication Systems (WFCS) (pp. 1-10). IEEE

[9] Schulz, P., Matthe, M., Klessig, H., Simsek, M., Fettweis, G., Ansari, J., ... & Puschmann, A. (2017). Latency critical IoT applications in 5G: Perspective on the design of radio interface and network architecture. *IEEE Communications Magazine*, *55*(2), 70-78.

[10] Nokia, "5G for Mission Critical Communication: Achieve ultrareliability and virtual zero latency," Nokia White Paper, 2016

[11] Rec, I. T. U. R. (2015). ITU-R M. 2083-0,". IMT Vision—Framework and Overall Objectives of the Future Development of IMT for, 2020.

[12] del Río, J. F. M., & Gandía, D. M. S. (2016). D1. 1 Refined scenarios and requirements, consolidated use cases, and qualitative techno-economic feasibility assessment.

[13] IEEE, «Amendment 5: Enhancements for Higher Throughput (802.11n),» Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, pp. 289-294, 2009.

[14] P. P. Bergmans and T. M. Cover, "Cooperative broadcasting," IEEE Trans. Inf. Theory, vol. 20, no. 3, pp. 317–324, May 1974.

[15] S. I. Park et al., "Two dimensional code based on low density parity check and Reed–Solomon codes for the terrestrial cloud transmission system," IEEE Trans. Broadcast., vol. 61, no. 1, pp. 75–83, Mar. 2015.

[16] Zhang, L., Wu, Y., Li, W., Kim, H. M., Park, S. I., Angueira, P., ... & Velez, M. (2014, June). Application

of DFT-based channel estimation for accurate signal cancellation in Cloud-Txn multi-layer broadcasting system. In Broadband Multimedia Systems and Broadcasting (BMSB), 2014 IEEE International Symposium on (pp. 1-6). IEEE.

[17] K.-J. Kim et al., “Low-density parity-check codes for ATSC 3.0,” IEEE Trans. Broadcast., vol. 62, no. 1, Mar. 2016.

[18] L. Zhang et al., “Performance characterization and optimization of mobile service delivery in LDM-based next generation DTV systems,” IEEE Trans. Broadcast., vol. 61, no. 4, pp. 557–570, Dec. 2015.

[19] S. Park et al., “Low complexity layered division multiplexing system for ATSC 3.0,” IEEE Trans. Broadcast., vol. 62, no. 1, Mar. 2016.

[20] D. Gómez-Barquero and O. Simeone, “LDM vs. FDM/TDM for unequal error protection in terrestrial broadcasting systems: An information theoretic view,” IEEE Trans. Broadcast., vol. 61, no. 4, pp. 571–579, Dec. 2015.

[21] Liu, J., & de Lamare, R. C. (2012). Low-latency reweighted belief propagation decoding for LDPC codes. IEEE Communications Letters, 16(10), 1660-1663.

[22] Stacey, R. (2008). Next Generation Wireless LANs. EP STACEY, Next Generation Wireless LANs, 185-215.

[23] Zhang, L., Li, W., Wu, Y., Wang, X., Park, S. I., Kim, H. M., ... & Montalban, J. (2016). Layered-division-multiplexing: Theory and practice. IEEE Transactions on Broadcasting, 62(1), 216-232.

[24] L. Zhang et al., “Application improved DFT-based channel estimation for accurate signal cancellation in cloud-Txn multi-layer broadcasting system,” in Proc. BMSB, Beijing, China, Jun. 2014, pp. 1–6

[25] Molisch, A. F., Balakrishnan, K., Cassioli, D., Chong, C. C., Emami, S., Fort, A., ... & Siwiak, K. (2004). IEEE 802.15. 4a channel model-final report. IEEE P802, 15(04), 0662.

[26] Miranda, J., Abrishambaf, R., Gomes, T., Gonçalves, P., Cabral, J., Tavares, A., & Monteiro, J. (2013, July). Path loss exponent analysis in wireless sensor networks: Experimental evaluation. In Industrial Informatics (INDIN), 2013 11th IEEE International Conference on (pp. 54-58). IEEE.

Annex I: Paper for IEEE Transactions on Industrial Electronics

NOMA-based 802.11n for Industrial Automation

Montalban, Jon, *Member, IEEE*, Iradier, Eneko, *Student Member, IEEE*, Val, Iñaki, *Member, IEEE* and Angueira, Pablo, *Member, IEEE*

***Abstract*— Industry 4.0 can be considered as the industrial revolution of the current century. Among others, one of its main objectives is the replacement of wired communications by wireless connectivity. The idea is to overcome the main drawbacks of the current wired ecosystem: the lack of mobility, the deployment costs, cable damage and the difficulties with scalability. However, for this purpose, the nature and requirements of the industrial applications must be taken into account. In particular, the proposed communications protocols must support very low loss rates and a strong robustness against failures. This is a very challenging condition due to the nature of the industrial environments (interference with other communication systems, reflections with metallic objects ...). In addition, another characteristic of the industrial applications is the strict requirement related to the latency. On the other hand, industrial applications are not only based on high challenging services, but also exist more flexible requirement applications, such as, web browser, email, video content or complementary information. Those services are considered Best Effort (BE) services. Eventually, given the need for a wireless communication system that meets the requirements of industrial applications and also includes the capability to efficiently deliver BE services, Layered Division Multiplexing (LDM) technology together with the IEEE 802.11g standard is proposed in this article as the physical layer solution. The IEEE 802.11n standard has been modified in order to accommodate the NOMA schemes, and then, comprehensive simulations are conducted to check and analyze the behavior of the proposed system. It has been determined that through LDM technology it is possible to obtain better results in certain cases than those achieved in a transmission cases that implements the IEEE 802.11n standard in TDM/LDM basis.**

***Index Terms*— Layered Division Multiplexing, NOMA, 802.11, local area networks.**

I. INTRODUCTION

THE forth industrial revolutions is driving the next evolution of the industrial communications. The main objective is to be able to wirelessly interconnect and computerize the traditional industrial environments, and consequently, improve the resources efficiency and the integration between processes and factories [1].

Currently, the major part of the machines are wired, even the increasing popularity of wireless services. The main reason is that it is not clear that the actual wireless standards could guarantee the tight requirements posed by the industrial applications.

A typical Industrial Wireless Sensor Network is depicted in Figure 1. The general centralized scenario is composed by several nodes (sensors), a sink/network controller, a management console and the process controllers. The nodes are in charge of the data collections and they communicate with the network manager, which eventually is communicating with the process controller. All the information delivery must share the same time and frequency resources. The exchanged data can be grouped into two different services. On the one hand, there is the real-time (RT) traffic with tight robustness requirements and loss intolerant, and on the other hand, there is the best effort (BE) traffic with less strict requirements and loss and delay tolerant. Consequently, very asymmetrical data services will be shared trough the network. In those cases, the Non Orthogonal Multiplexing Access (NOM) techniques are much more efficient than the traditional TDM/FDM schemes [2].

The 802.11 family of wireless standards were not designed for the development of industrial communications. Nevertheless, in the last few years, the study of the possible use of the 802.11 standard for industrial communications has rapidly increased. One of the main advantages is that the 802.11 is based on the same standards framework as Ethernet and this provides a high level of interoperability and ensures that Ethernet/WLAN internetworking functions. Nevertheless, the weak point is its medium access mechanism, CSMA/CA, does not guarantee deterministic behavior, so it is difficult to ensure real-time services in a crowded spectrum [6].

In fact, the medium access technology is one of the key factors that determine the success in industrial communications. That is why some researches has been carry out for different kind of medium access. In [4], a soft

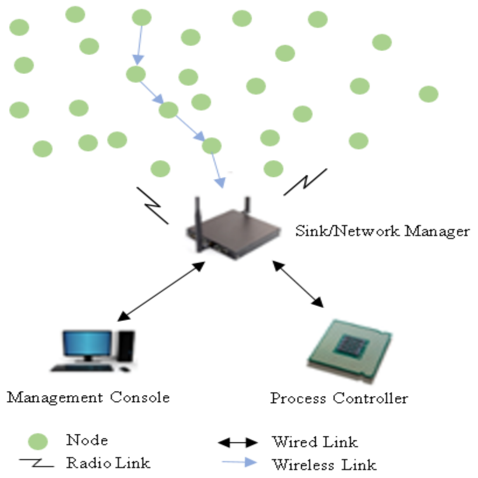


Fig. 1. Typical Industrial Wireless Sensor Network in an Industrial Environment.

real-time control system is presented based on CSMA, for none strict temporal requirements. First, the system is modeled and then, the effects of caused by using the communication network are statistically presented. Another interesting approach is presented in [5], where a hybrid approach between contention-based and time schedule-based protocols is proposed. It is proposed to use spatial TDMA for each cluster.

Aiming at covering the two topics pointed out previously, this paper proposes the joint use of NOMA techniques and the 802.11n standard in order to fulfill the main requirements of the next generation Industrial 4.0 applications. Even if there have been some attempts to include NOMA based solutions in the industrial communications this paper is the first proposal, which offers a complete performance evaluation, from the PHY evaluation to the PER analysis of the MAC layer [6].

The paper is organized as follows. The next section describes the characteristics and requirements of the industrial communications. Section III LDM technology based on 802.11n standard. Section IV discusses differences on capacity and thresholds between the original and the modified standard and gives a comparison with TDM. Section V describes the proposed system performance. Section VI presents a realistic use cases and a MAC layer level validation. Section VII contains the conclusions.

II. INDUSTRIAL COMMUNICATION TECHNOLOGIES AND REQUIREMENTS

This work proposes a robust communications system for industrial applications. First of all, a deep literature study has been carried out, where on the hand, the two mainly used standard families for industrial communications have been studied (802.11 and 802.15), and on the other hand, the characteristics and requirements of the industrial communications have been analyzed.

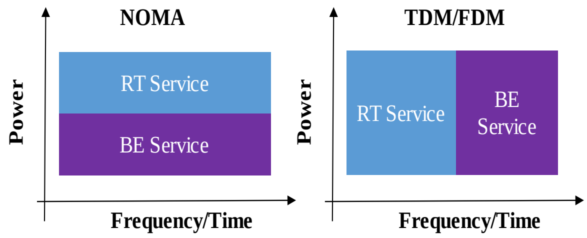


Fig. 2. Non-Orthogonal Multiplexing (OMS) schemes sharing both the time and frequency resources.

802.15 is a working group inside the IEEE 802 specialized in Wireless Personal Area Networks (WPAN). The good characteristics of this family are low energy consumption and support for several different topologies, which makes it a good candidate for industrial communications. However, some of the well-known cons are low scalability within a specific cycle time and low data rate [8]. Despite the disadvantages, several studies have been done in order to integrate this technologies in industrial environments. In [9], a specific scheduling algorithm, Multichannel Superframe Scheduling (MSS), is presented for cluster-tree architectures based on IEEE 802.15.4 communications. This technique has been tested and compared with traditional time division superframe scheduling techniques. Moreover, in [10] the cross-channel interference is taken into account for the 802.15.4 systems, since, it is one of the main disadvantages of using multiple radio channel communication systems. This paper offers a deep explanation of this kind of interference and a general methodology for the assessment of IEEE 802.15.4 performance under different cross-channel interference conditions. In [11] and [14], one of the main goals of the industrial communications appears, strict real-time communications. Different algorithms are presented and evaluated by simulations and experiments for IWSN.

In addition, when very low data rate industrial applications are developed, 802.15.4 standard fixes accordingly to the requirements. In [13] a set of simulation is presented, showing the benefits and the limitations of the standard. Timing, consumption and reliability related parameters are measured. Finally, in [14] a simulation based study has been done for the LR-WPAN standard using an OMNeT++ model for industrial communication environments. Different scenarios has been evaluated in terms of latency and energy consumption.

As it has already been said, another technology that has been used with industrial perspective is the 802.11 standard family. In this case, in comparison with 802.15 family, higher data rates are easily achieved. Some literature is available implementing this technology for industrial communications. For example, in [15] typical applications based on fieldbus protocols, such as Master-Slave architectures, are studied in order to integrate them on top of the IEEE 802.11 standard. These applications are mapped onto the wireless standard services and a theoretical model of the communication system is presented to evaluate typical performance parameters. In [16] in order to achieve strict reliability and timing values for industrial communication systems, rate adaptation techniques are tested in some commercial IEEE 802.11 devices and it is compared with a general purpose widespread technique. In [17], the design principles and the implementation details of a new wireless communication protocol for real-time applications is presented. RT-WiFi is a TDMA-based protocol and offers determinism and high sampling rate using the 802.11 standard physical layer. It has configurable parameters and its performance has been tested in terms of latency and reliability. Finally, in [18] IEEE 802.11n standard, one of the latest version, has been evaluated. The main objective of this work is to test this standard for industrial real-time communications and to determine a set of suggestions for the useful implementation of the standard in industrial environments in terms of reliability and latency.

Taking into account more recent literature, there are some cross layer approach, not only from a PHY-MAC point of view, but also from the network point of view. In [19] different aspects that have to be taken into account for the design of ultra high-performance wireless networks for critical industrial control applications are detailed. In [20], SHARP (Synchronous and Hybrid Architecture for Real-time Performance) is presented, a new architecture for industrial automation. Its wireless part includes a novel PHY layer based on 802.11g integrated in a TDMA in order to guarantee determinism.

As could be seen in the above lines, lots of implementations are available in the literature in order to achieve real-time and low latency industrial communications. However, there is not still a clear winner technology and there are very dependent of the application.

Regarding the possible application sectors, in general, nowadays industry has two main application sectors: Factory Automation (FA) and Process Automation (PA).

On the one hand, FA concept refers to industrial communications in which it is necessary to control machines or complete systems in real-time. Generally, these types of communications are related to production chains, where machines are fundamental elements of the process. Some representative examples of this type of industry would be: assembly, packaging, palletizing or manufacturing, among others. Due to the relevance of these communications in their respective processes, they are very sensitive to errors and latencies, so low values of latency (0.25-10 ms) and packet loss rates (10^{-9}, implementing retransmissions) are required. In addition, the update time is between 0.5-50 ms and the coverage areas are around 50-100 meters radius [21] [22].

On the other hand, PA concept refers to industrial communications in which applications for monitoring and diagnosing of elements and processes are included. As an example of PA typical fields heating, cooling, stirring, pumping procedures or machinery condition monitoring could be listed. One of the main differences compared to FA is that the variation of the measured values is slower, so the requirements are in turn more relaxed. As for the most representative requirements, that is, latency and reliability, they are placed around 50-100ms and 10^{-3}-10^{-4} packet loss rate, respectively. Moreover, for the update time 0.1-5 seconds are required and the communications ranges vary between 100 and 500 meters [21] [22].

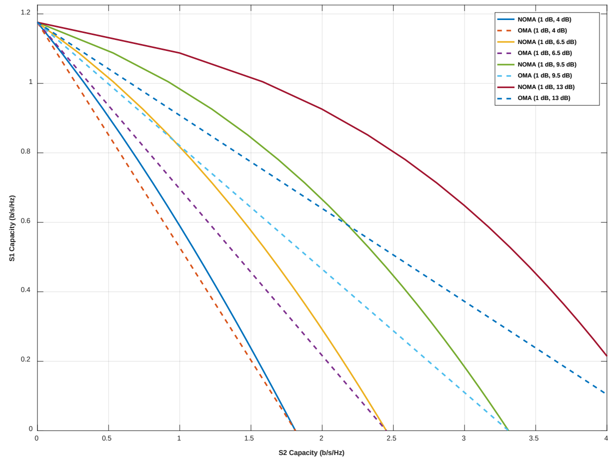


Fig. 3. Theoretical LDM/TDM comparison

III. NOMA-BASED 802.11N

A. Non-Orthogonal Multiplexing Access (NOMA)

General speaking, the NOMA delivery consists on a signal ensemble composed of several layers, each one taking a portion of the total power delivered by the transmitter. Each layer is configured targeting different robustness levels, decoding thresholds and capacities; depending not only on the modulation and coding, but also on the power distribution. The power splitting can be described by the parameter Δ (injection level, measured in decibels). The multiple layer signal concept for two services is shown in Figure 2 and the general frequency domain NOMA signal ensemble can be expressed as:

$$x_{NOMA}(k) = x_{RT}(k) + g \cdot x_{BE}(k) \qquad (1)$$

where $x_{RT}(k)$ and $x_{BE}(k)$ are the two data streams combined into $x_{NOMA}(k)$ and k is the subchannel index. The injection level g defines the linear power allocation ratio between layers.

The idea of multiple signals on the same channel with unequal error protection was described decades ago by information theory papers [23]. However, the application of the concepts into real equipment has been only feasible lately. One of the drivers for feasibility is the developments in error coding and specifically, the remarkable advances in Low Density Parity Check (LDPC) codes [24]. The

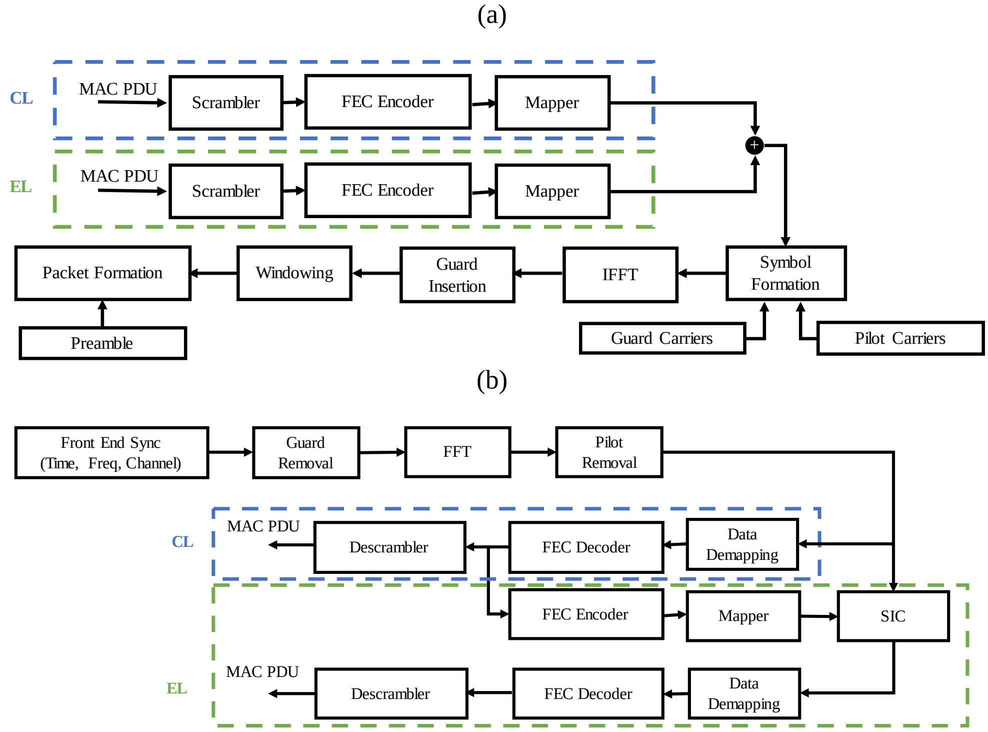


Fig. 4. General block diagram of the proposed transceiver. From up to bottom: (a) NOMA 802.11 n generator with NOMA, (b) Enhanced NOMA 802.11 n receiver with NOMA.

latest LDPC codes performance is closer than half a dB from the Shannon curve [25]. The second driver for feasibility is the newly implemented signal cancellation structure proposed in [26] that, taking advantage of the structure of the LDPC matrix proposed in simplifies the complexity of the receiver significantly [27].

Based on that, in 2017 the North American ATSC 3.0 digital terrestrial television (DTT) standard included a low-complexity solution based in NOMA for the efficient delivery of low capacity and high capacity services in the same RF channel. LDM has undergone intense research work during the last years under the umbrella of the standardization process of the next generation broadcast standard ATSC 3.0 [25] to [29].

In Figure 3, there is a graphical comparison of the spectral efficiency of NOMA and traditional TDM/FDM schemes from the information theoretic point of view when two services are delivered in the same time and frequency resources [26]. The solid lines depicted the spectrum efficiency in terms of bps/Hz for the NOMA based solutions, where the dashed lines stand for the TDM/FDM services. Each pair of curves represent the maximum achievable capacity assuming different SNR thresholds for each service. For instance, the solid blue line (NOMA) and the dashed orange line (TDM/FDM) compare the maximum spectrum efficiency of both cases when the low-throughput SNR is targeting 1 dB and the high-throughput is targeting 4 dB. In this case, the maximum gain is only about 0.1 bps/Hz. Nevertheless, if the services reception thresholds are unbalanced (solid red and dotted blue lines), the overall gain offered by NOMA can be up to 1 bps/Hz. In practice, NOMA will outperform TDM/FDM providing that the FEC performance is optimal enough.

Last, but key for system feasibility in industrial environments, processing time and resource requirements at the receiver require special attention. Industrial communication systems are typically rolled out for supervision and control purposes where security, reliability and delay will be critical design constraints. NOMA directly addresses security and reliability based on close to zero and even negative reception thresholds for one of the services. Flexible configuration of layers also is an advantage for increasing the security of the physical layer. On the contrary, the cancellation associated to additional layer decoding involves additional processing latency on the receiver. The specific error coding technique is the key factor to this respect [30]. Some reference works are available in the literature. In [27], the latency associated to large LDPC codes was analyzed. The results show that the number of iterations of the LDPC decoding algorithm remains below 5 for SNR values below 4-5 dB, making the associated decoding time not relevant on the overall OFDM receiver processing time budget, mostly influenced by MAC operations. Nevertheless, it should be noted that time requirements cannot be described on a general basis and each application scenario requires a thorough analysis of the control-cycle vs. receiver processing time. This paper focuses on system feasibility and potential reliability/throughput advantages over

TDM/FDM systems.

B. 802.11n

A relevant portion of industrial communication applications tends to use wireless systems based on 802.11 and 802.15 standards families. One of the main advantages of the 802.11 group is the higher throughput and the coverage range that it can provide. The 802.11n standard appeared as an evolved version of the existing 802.11g version in order to offer higher throughput datarates. This older version was as well an improvement of the existing versions, since the 802.11b standard has a maximum transmission rate of 11 Mbps, and the 802.11a standard only operates in the 5 GHz band. Therefore, the 802.11g variant offers a transmission rate comparable to the 802.11a version (up to 54 Mbps) while allowing operation in the 2.4 GHz band. Although it conserves many characteristics of its forerunners, such as for example the CSMA/CA access to the medium, it also incorporates significant improvements achieved through physical velocities of up to 600Mbps. In this work, the latest 802.11 ac is not considered as their main contribution, based on high datarate services, are not relevant for these scenarios.

Regarding the 802.11n, the main reason to achieve those high theoretical throughputs is by using MIMO. This standard provides Spatial Division Multiplexing (SDM), which spatially multiplexes multiple independent data streams, transferred simultaneously within one spectral channel of bandwidth. Although this standard allows the use of that different transmission technique, throughout this paper only SISO transmissions have been worked with. The main reason is that the reliability is the key performance indicator for this scenarios.

These transmissions are carried out over a 20 MHz bandwidth, where there are 64 carriers: 8 null, 4 pilot carriers and the remaining 52, data carriers. From these data, it is deduced that the space between carriers is 312.5 kHz and the useful bandwidth is 17.8 MHz. Therefore, since the symbol time is the inverse of the space between carriers, 3.2 µs of symbol time are established. In addition to that, 0.8 µs are added to each symbol as guard interval to reduce intersymbol interference, so that the total symbol time is 4 µs. Moreover, optionally a 40 MHz bandwidth could be used, which enhances the overall offered throughput.

As for the modulation and coding applied to each transmission, the standard itself defines 8 pre-established transmission modes. Those modes vary between BPSK, QPSK, 16-QAM and 64-QAM modulations, to which depending on the case, a Code Rate of 1/2, 2/3, 3/4 or 5/6 can be applied. Each of the available combinations is called MCS (Modulation and Coding Scheme). Due to these configurations, the capacity offered by each of the MCS varies between 6 Mbps (MCS0) and 60 Mbps (MCS7).

There are two operating modes in the 802.11n standard, one for High-Throughput (HT) solutions and another one for Non-HT solutions, Greenfield and Mixed Mode, respectively. Greenfield mode can only be used when no legacy devices exists in the network. An 802.11n device using Non-HT mode sends every packet in the old 802.11a/g format so that the other devices can understand it. That device must use 20 MHz channels and none of the new HT features. One of the responsible for the throughput improvement and for the SNR threshold value reduction in comparison with the 802.11g standard are the FEC implemented, the LDPC codes specifically. The IEEE 802.11n wireless standard involves three sub-blocks (27, 54, and 81 bits) and four code rates (1/2, 2/3, 3/4, and 5/6). Hence, 12 different Z x Z sparse matrices can be selected [31].

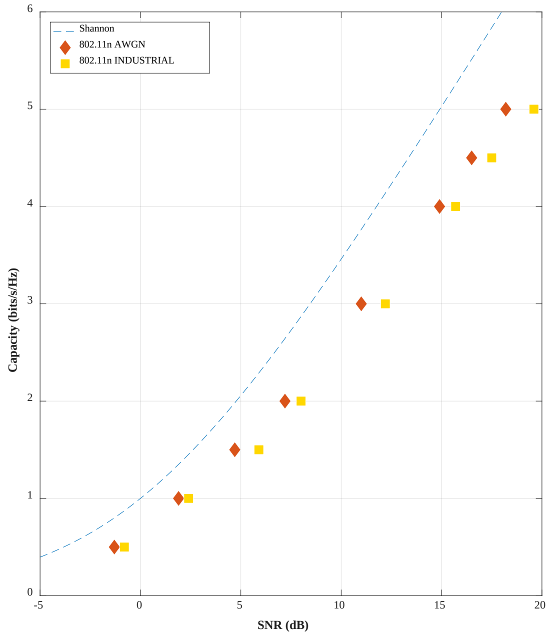


Fig. 5. One layer SNR threshold for the 802.11n at PER 10^{-3} for AWGN and industrial channel.

In order to carry out the Medium Access Control (MAC), as in Ethernet, CSMA (Carrier Sense Multiple Access) protocol is used, which consists in detecting the channel. When it is inactive, it begins to transmit, emitting its complete frame and without listening to the channel in the process, which could cause collisions. To avoid such collisions and data corruption, the 802.11 uses Collision Avoidance (CA) system, in conjunction with CSMA, this consists in counting the channel repeatedly to detect when it is free of other transmissions.

Physically, the CCA (Clear Channel Assessment) is used, which is a message indicating the state and the method of virtual channel sensing. Once it is free, warning messages are sent through it in order to avoid collisions. In case of collisions there are random waiting times that increase according to the Exponential Backoff algorithm.

C. LDM on 802.11n

TABLE I
TRESHOLD COMPARISON (dB)

LDM				TDM /FDM			
CASE A CL (6 Mbps) EL (12 Mbps)	LDM (IL =-4dB)			CASE A CL (6 Mbps) EL (12 Mbps)	CL (%50) / EL (% 50)		
	MCS	AWGN	INDUSTRIAL		MCS	AWGN	INDUSTRIAL
	BPSK 1/2	1.7	2.5		QPSK 1/2	1.9	2.4
	QPSK 1/2	7.4	7.9		16-QAM 1/2	7.2	8
CASE B1 CL (6 Mbps) EL (24 Mbps)	LDM (IL = -6,5dB)			CASE B1 CL (6 Mbps) EL (24 Mbps)	CL (%50) / EL (% 50)		
	MCS	AWGN	INDUSTRIAL		MCS	AWGN	INDUSTRIAL
	BPSK 1/2	0.4	1.1		QPSK 1/2	1.9	2.4
	16 QAM 1/2	14.7	15.5		64-QAM 2/3	14.9	15.7
CASE B2 CL (6 Mbps) EL (24 Mbps)	LDM (IL =-2.5 dB)			CASE B2 CL (6 Mbps) EL (27 Mbps)	CL (%25) / EL (% 75)		
	MCS	AWGN	INDUSTRIAL		MCS	AWGN	INDUSTRIAL
	BPSK 1/2	3.0	4.0		16-QAM 1/2	7.2	8.0
	16 QAM 1/2	11.7	12.5		16-QAM 3/4	11	12.2
CASE C CL (6 Mbps) EL (36 Mbps)	LDM (IL =-4.0)			CASE C CL (6 Mbps) EL (36 Mbps)	CL (%33) / EL (% 66)		
	MCS	AWGN	INDUSTRIAL		MCS	AWGN	INDUSTRIAL
	BPSK 1/2	1.7	2.1		QPSK 3/4	4.7	5.9
	16 QAM 3/4	16.7	18.2		64-QAM 3/4	16.5	17.5
CASE D CL (6 Mbps) EL (48 Mbps)	LDM (IL =-1,5dB)			CASE D CL (6 Mbps) EL (48 Mbps)	CL (%20) / EL (% 80)		
	MCS	AWGN	INDUSTRIAL		MCS	AWGN	INDUSTRIAL
	BPSK 1/2	4.3	4.7		16-QAM 3/4	11	12.2
	64QAM 2/3	18.9	20.20		64-QAM 5/6	18.2	19.6

In this paper, it is proposed the jointly use of 802.11 standards family and NOMA as a solutions to address the challenges of industrial wireless environments. In particular, it is proposed to modify the 802.11n standard to include LDM as a multiplexing solution, which can be understood as a low complexity NOMA case. Consequently, the architecture proposed in this paper tries to minimize the complexity associated to a non-orthogonal receiver.

The transmitter side is composed of an adaptation module that prepares data for the error coding stage (see Fig 4 (a)). Previous work already assessed the relevancy of a proper choice of the data overlapping for efficient and simple receiver implementation [27]. For the sake of simplicity and compatibility with further experiments on the 802.11 family, FEC scheme is the same proposed in IEEE 802.11g/n [31]. If the system uses OFDM waveforms and the framing structure of each one of the layers are synchronized, the receiver complexity and latency remains acceptable. The mapping and framing stage are inherited directly from 802.11n Modulation and Coding Schemes (MCS). The only difference is that after mapping, both services are combined into a single stream. The next stages are equivalent for both services as they are one ensemble. The final physical waveform are PHY packets composed of a preamble and a data field. The detailed structure of the PHY packet is maintained as defined in 802.11n. However, there is one additional requirement: the packet length of the enhance layer service is selected in order to match the same number of symbol per frame that the core layer service. In general, the EL PSDU length should be calculated as:

$$PSDU_{EL} = \lfloor (Sym_{Num} * NDBPS_{EL} - N_{Service})/8 \rfloor \quad (2)$$

In order to test the proposal, a transmitter and receiver chain fully compliant with the 802.11 a/g/n standard has been implemented. Afterwards, several modifications have been introduced in the transceiver chain in order to make it possible to multiplex services in NOMA basis (See Fig. 4).

First, at the MAC layer the two different layers PSDU packet length is theoretically adjusted in order to assure that they will require the same numbers of symbols per frame. Consequently, after the mapping block a NOMA simplified approach could be used, and thus, the BE receiver complexity will be greatly reduced. Afterwards, the transmitter block has been updated according to Figure 6 (a) to power multiplex two different services.

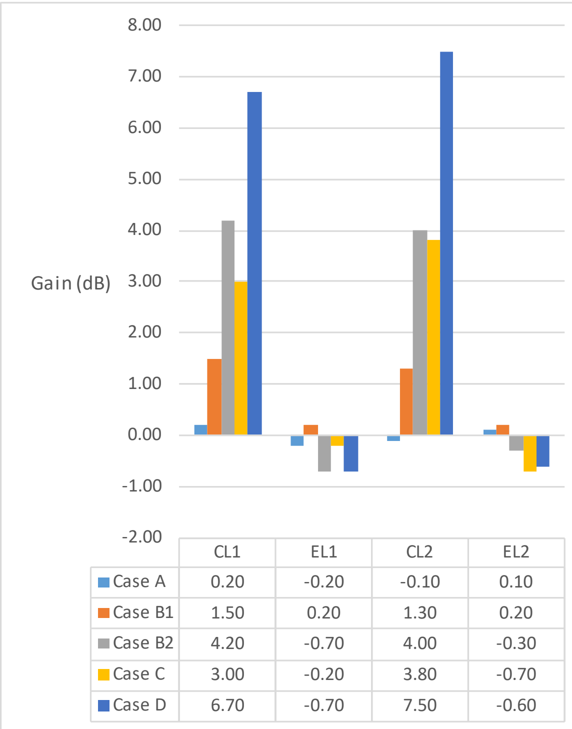
Being a comparative study, firstly, the less challenging AWGN channel is implemented as a propagation channel, and, secondly, a static industrial channel model with Non-Line-Of-Sight (NLOS) condition and 29 ns rms delay spread is included [34].

At the receiver, an H-SIC cancellation algorithm is added to the well-standardized 802.11n receiver (See Fig. 6 (b)). Perfect synchronization and channel estimation are considered.

The performance is evaluated through Packet Error Rate (PER), which is the key performance indicator in industrial applications. In particular, for each SNR value more than 5000 packet are tested. A PSDU packet is considered erroneous is any of the bits are decoded incorrectly. Finally, it must be noted that the simulation step is 0.1 dB.

B. One Layer Performance

As part of the performance analysis, first, the single layer simulations are studied. The main objective is to test the ideal receiving thresholds of the single service, which



	CL1	EL1	CL2	EL2
Case A	0.20	-0.20	-0.10	0.10
Case B1	1.50	0.20	1.30	0.20
Case B2	4.20	-0.70	4.00	-0.30
Case C	3.00	-0.20	3.80	-0.70
Case D	6.70	-0.70	7.50	-0.60

Fig. 6. Results summary for the NOMA TDM/FDM gain.

afterwards will be used as a reference for the TDM vs NOMA comparison.

The results are gathered in Fig. 5. The receiving thresholds at PER 10^{-3} are plotted for the different MCS values for both the AWGN and INDUSTRIAL channel models. In addition, the Shannon-Harthley ideal capacity has been included in order to show the efficiency of the implemented LDPC codes. General speaking, the graphic shows that the distance from Shannon for the AWGN case is between 1 and 2 dB depending on the MCS selection. Therefore, it can be assumed that the FEC efficiency is enough to maintain the NOMA gain versus the orthogonal methods [35]. What is more, it can be also seen that for a multipath environment the difference with respect to the AWGN channel ranges from 0.5 to 1 dB, and consequently, the proposed NOMA based 802.11n can be implemented in an industrial environments.

C. Two Layer Performance (NOMA, OMA)

Once that the platform has been validated the next step is to test the NOMA proposal and compare de results with the traditional TDM/FDM non-orthogonal schemes.The obtained results have been gathered in TABLE I.

In order to give a general overview there have tested five different uses cases, which assures the required trade-off between throughput and robustness for industrial applications. For instance, the RT service is offered trhough the most robust MCS configuration targeting a throughput of 6 Mbps. It is expected that it will guarantee the required critical bitrate for connecting several clusters of sensors. Afterwards, there have proposed five different configurations for the BE service. The aiming at covering different multimedia services ranging from 12 to 48 Mbps.

In the NOMA case, each of the uses cases has its own injection level, which have been selected in order to maximize the gain for the RT service, even if the BE threshold could be slightly degraded. In the TDM/FDM case, it must be taken into account that the critical service can only allocate a percentage of the total resources, and thus, the rest should be dedicated to BE communications. For instance, in the CASE A the time is split equally between the two services, and consequently, you need a bitrate of 12 Mbps to satisfy a 6 Mbps demand. Finally, it must be noted that in some cases it has not been possible to match exactly the results.

The TDM/FDM based services thresholds are directly obtained from the values presented in the previous section, whereas the NOMA based thresholds are simulated following the same rules as applied before. The values offered for NOMA can be also obtained theoretically introducing the one-layer results in the formulas presented in [26]. In fact, the values obtained with the formulas are in line with the presented results, being the deviation always less than 0.4 dB.

The results have been obtained for both the AWGN and the INDUSTRIAL multipath channels. The PPDU size of the TDM/FDM services and the LDM services has been matched to be sure that the same configurations also share the same FEC coding procedures.

Eventually, in order to make easier the comparison the NOMA gain against traditional TDM/FDM services has plotted in Fig.6.

First of all, it must be note that for the critical service the gain ranges from 0.2 to 6.7 dB in the AWGN case, and from 0.1 to 7.5 in the industrial channel case. Therefore, the first conclusion is that the NOMA gain is even higher in the most challenging scenarios. Apart from that, it is interesting to see how the NOMA gain for asymmetrical services, the more unequal the services bitrate the higher the gain. On the other hand, it can be seen that there is also a small loss for BE services. Nevertheless, this is not an issue as the RT is much higher and much important, as we will see in the next section.

In short, the NOMA approach shows a remarkable SNR gain for RT services, which increases with the capacity inequality among layers. The bigger the data throughput asymmetry the bigger the NOMA gain. Eventually, it is also important to note that the proposed SNR thresholds are always smaller than 20 dB.

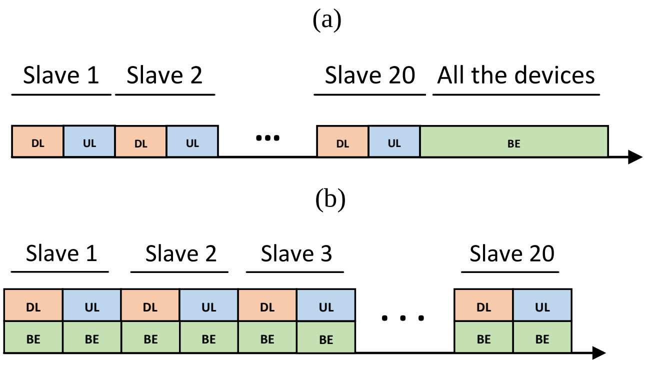


Fig. 7. Time schedule representation. From up to bottom: (a) TDMA, (b) LDM

TABLE II
SIMULATED CONFIGURATIONS

Case	MCS	RT segment (ms)	BE segment (ms)	Tcycle (ms)
A – NOMA	0 & 1	7.2	7.2	7.2
A – TDMA	1 & 3	3.6	3.6	7.2
B1 – NOMA	0 & 3	7.2	7.2	7.2
B1 – TDMA	1 & 5	3.6	3.6	7.2
B2 – NOMA	0 & 3	7.2	7.2	7.2
B2 – TDMA	3 & 4	1.8	5.4	7.2
C – NOMA	0 & 4	7.2	7.2	7.2
C – TDMA	2 & 6	2.4	4.8	7.2
D – NOMA	0 & 5	7.2	7.2	7.2
D - TDMA	4 & 7	1.44	5.76	7.2

V. Industrial use case and MAC performance analysis

A. Use case

In this paper, the proposed technical solutions is evaluated under a manufacturing plant. In particular, a network architecture is proposed with a central node (Access Point, AP) located in the center of the plant and 20 slave nodes distributed randomly along the extension (See Fig.7). In this case, slaves represent the sensors or actuators, whereas the AP is the master node of both the architecture and the synchronization, and distributes information to all the devices connected in the network. As mentioned above, when a comparison is made between a 802.11n standard based on TDMA medium access and another 802.11n standard based on LDM technique, it is necessary to specify the time schedules to be followed for of the cases for an ordered medium access. Thus, the following hypothesis is fulfilled. For the TDMA system, traffic of a single type is transmitted in each of the slots, as it is shown in Figure 7 (a). On the other hand, for the LDM system, in each time slot both types of traffic are transmitted, placing the RT traffic in the core layer and the BE traffic in the enhance layer, as it is shown in Figure 8 (b).

In addition, a distinction between downlink (DL), from AP to Slave, uplink traffic (UL), from Slave to AP, and RT and BE traffic. Hence, there are four types of traffic that has to be organized must be done. In TDMA systems, the superframe is divided into two main blocks, the RT traffic transmission slots and the BE traffic block. Regarding the RT traffic, the medium access is ordered, so that a specific time is dedicated to each slave, consisting of two slots, one for DL traffic and the other for UL traffic. Once the communication with all the slaves has been made, the space for the BE traffic transmission starts. In this case, the access is achieved by contention, and the duration of this traffic block is according to the distribution of established times, for instance, in the cases of TDM %50 - %50, the duration of the BE traffic block is equal to the RT communication with the 20 nodes. An example of the TDMA system time distribution is shown in Figure 7 (a).

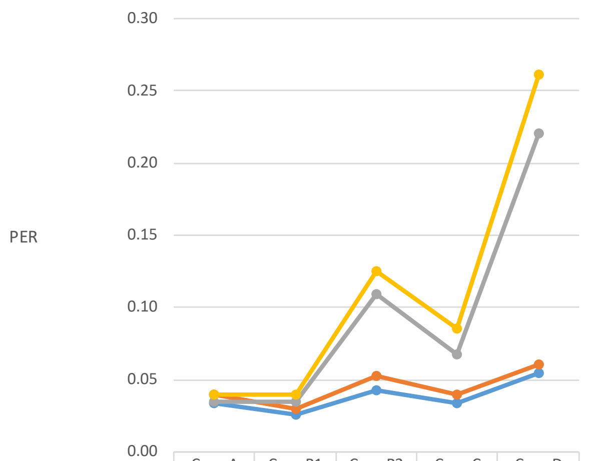
On the contrary, in LDM systems, traffic has to be restructured. In this way, the superframe is only divided by nodes, and during each of these divisions, there is a complete communication between the AP and the respective slave. In this case, the medium access is completely ordered for both RT and BE traffic, since they are transmitted in the same time slot using the upper and lower layers, respectively. The slot size for this technique is equal to the amount of time the upper layer package is in air, and, so, the amount of data transmitted in the lower layer is adapted to match the RT layer air time. An example of the LDM system time distribution is shown in Figure 7 (b).

The time taken to transmit an LDPC block with the lowest MCS (BPSK 1/2) has been taken as reference, 180 µs. During this time slot, using LDM, both the RT and BE services are transmitted. However, for TDMA-based cases, the 180 µs are shared between RT traffic and BE traffic depending on the time distribution used (TABLE II). In this way, the information transmitted in relation to each type of traffic is the same for both multiplexing mechanisms, with the time distribution and injection level being the parameters that define the amount of data delivered for each service. Hence, a complete cycle time has always fix duration, which is equal to 40 LDM time slots (Figure 8b), 7.2 ms. Due to that cycle time length, the update time requirements that are established for industrial communications and detailed in Section II are met. TABLE II shows the composition of the cycle time of each of the proposed study cases.

The selected MCS combinations are consistent with the results offered in the previous section (See Table II). In order realistic results, more than twenty simulations have been carried out with each configuration, varying the seed to obtain different space distributions of the equipment. Each of the nodes transmits 10 dBm. The simulated area is 100x100 meters long and the path loss exponent is set to 2.5 to fix with industrial indoor communications [36].

B. Simulation Methodology

In this section, the work presented in the previous section is completed with a network simulator, namely OMNeT++ [37]. First of all, the PER curves obtained in



	Case A	Case B1	Case B2	Case C	Case D
NOMA - AWGN	0.034	0.026	0.043	0.034	0.054
NOMA - IND	0.040	0.030	0.053	0.040	0.060
TDMA - AWGN	0.035	0.035	0.109	0.067	0.221
TDMA - IND	0.040	0.040	0.125	0.085	0.261

Fig. 8. RT traffic PER

the previous section for different channel models at different SNR thresholds are loaded in OMNeT++. Secondly, a typical industrial propagation area is included represented by a Rayleigh model. Afterwards, the program estimates the energy balance of a set of randomly located sensors points giving the SNR which is based on the distance between the devices that communicate and on the path Rayleigh fading. This two entries are fed to the model and there it is calculated which is the probably of a packet to be erroneous.

C. Results

The results are gathered in Figure 8 and Figure 9. First of all, for the AWGN channel simulations, it should be noted that NOMA based RT services are more robust than TDMA based ones. In fact, LDM-based architectures obtain for each case a PER below 10^{-1}, since in some cases those values are closer to 10^{-2}. In addition, although different cases are evaluated, NOMA always offers a similar reliability performance. However, in TDMA-based architectures it can not be always obtained a PER lower than 10^{-1} and the success rate obtained in the last three cases is not enough to guarantee the correct transmission of the RT service. It is important to highlight that in TDMA-based simulations, there is not a constant trend on the obtained PER as it happens in NOMA, and so, there are only available the first two cases, while using NOMA, each of the cases could be implemented. Definitely, this implies a considerable increase in the reliability of the communication. However, for BE services results trend is opposite. In this case, services LDM-based systems have a higher error rate, although this traffic type characteristics are not as strict as RT traffic ones, so that success different is assumable. Secondly, in the industrial channel case, it can be seen that although the results generally contain a greater number of losses, because the necessary thresholds are higher, the trend remains. That is, the NOMA-based systems offer a large increase in the robustness of the RT

	Case A	Case B1	Case B2	Case C	Case D
NOMA - AWGN	0.118	0.437	0.275	0.556	0.673
NOMA - IND	0.133	0.478	0.308	0.635	0.730
TDMA - AWGN	0.114	0.414	0.227	0.486	0.591
TDMA - IND	0.130	0.459	0.268	0.535	0.645

Fig. 9. BE traffic PER

services and a greater number of losses in the BE services. Moreover, in LDM-based cases, always is achieved a lower PER than 10^{-1}, while for TDMA-based cases, again, only twice is achieved and the last three cases are not possible due to the high loss rate in the critical service.

In addition, it is important to highlight the role played by each of the services and the requirements they have. Therefore, it is extremely important to increase the robustness of the RT services; for instance, if synchronization information is send by RT services, a failure in the transmission can result in the loss of an entire superframe, that is, that the packet losses in the information of synchronization directly affect BE traffic and other RT traffic.

It should be noted that in this first step of this new technology integration, retransmissions are not included. That is why, PER values are not as low as the ones mentioned in Section 0. However, implementing retransmissions in this NOMA-based communication system is an interest topic, and taking as a reference works that apply for a similar environments, as [19], depending on the redundancy level of the retransmissions, a MAC level PER of 10^{-8} is affordable for the PHY level PER values presented in Section 0.

Although it was not one of the main objectives, due to the temporary reorganization of the services, a considerable gain in determinism has been obtained for BE services. Using NOMA techniques, as BE services are transmitted in the lower layer and they are aligned with RT services, which need high reliability, it is much easier to determine the timing of the transmission and the reception of each BE package, and therefore, it is easier to predict their latency, among other parameters.

VI. Conclusion

In this article, we provide a comprehensive proposal of an NOMA-based 802.11n architecture for IWSN. In addition to the necessary theoretical basis and the design of the proposal, a simulation setup has been presented at PHY level. Moreover, the data obtained through the setup has been validated with a realistic industrial use case and the impact at MAC level has been studied.

In general, LDM offers better results, since, on the one hand, as shown in Section 0, the robustness of the RT services is highly increased, and on the other hand, the flexibility in the characteristics of the services offered is increased, since that using TDMA there are MCS combinations that can not be offered.

In spite of this, it is true that in some cases TDMA-based systems offer slightly better results in some aspects, especially for BE services. As already mentioned, this is mainly due to the numerology of the 802.11n standard modes is critical in the offer of LDM, since few modes are offered and they are not unbalanced enough to obtain maximum efficiency.

However, it is important to emphasize that in all the proposed scenarios, an important improvement is obtained in one of the main characteristics of industrial communications: the reliability of RT services. In fact, NOMA-based simulation losses are always constant between 10^{-1} and 10^{-2} PER values, where TDMA does not guarantee that constant behavior, concluding with some non-implementable cases due to the high loss rate.

It is also essential to emphasize that the concept of robustness is much more important in RT services than in BE services, since an error in the RT packages can cause errors in the rest of the super frame, involving not only BE traffic, but also RT traffic. In addition, by using this proposal, an extra advantage is obtained with respect to TDMA: determinism in BE services. It is true that this is not one of the main objectives in industrial communications; however, concepts such as latency become predictable.

Finally, as a future work, it would be interesting to validate this proposal in an industrial environment with real hardware. Hence, how to implement this proposal in commercial devices would be studied and creating compatible transceivers with NOMA technology.

References

[1] A. Varghese y D. Tandur, «Wireless requirements and challenges in Industry 4.0,» de International Conference on Contemporary Computing and Informatics (IC3I), Mysore, India, 2014.

[2] S. M. R. Islam, N. Avazov, O. A. Dobre and K. Kwak, "Power-Domain Non-Orthogonal Multiple Access (NOMA) in 5G Systems: Potentials and Challenges," in *IEEE Communications Surveys & Tutorials*, vol. 19, no. 2, pp. 721-742, Secondquarter 2017.

[3] Fernandez, Z., Cruces, C., Val, I., & Mendicute, M. (2017, May). Deterministic real-time access point concepts for industrial hybrid Ethernet/IEEE 802.11 networks. In Electronics, Control, Measurement, Signals and their Application to Mechatronics (ECMSM), 2017 IEEE International Workshop of (pp. 1-6). IEEE

[4] Tavassoli, B., Jabehdar-Maralani, P., & Rezaee, N. (2009). Tuning of control systems over CSMA networks. IEEE Transactions on Industrial Electronics, 56(4), 1282-1291.

[5] Le, H., van Eck, J., & Takizawa, M. (2013). An efficient hybrid medium access control technique for digital ecosystems. IEEE Transactions on Industrial Electronics, 60(3), 1070-1076.

[6] E. Arruti, M. Mendicute y M. Barrenechea, «Unequal error protection with LDM in inside carriage wireless communications,» IEEE, 2017.

[7] M. Bal, «Industrial Applications of Collaborative Wireless Sensor Networks: A Survey,» de IEEE 23rd International Symposium on Industrial Electronics (ISIE), Estambul, Turquía, 2014.

[8] Gungor, V. C., & Hancke, G. P. (2009). Industrial wireless sensor networks: Challenges, design principles, and technical approaches. IEEE Trans. Industrial Electronics, 56(10), 4258-4265.

[9] Toscano, E., & Bello, L. L. (2012). Multichannel superframe scheduling for IEEE 802.15. 4 industrial wireless sensor networks. IEEE Transactions on Industrial Informatics, 8(2), 337-350.

[10] Bello, L. L., & Toscano, E. (2009). Coexistence issues of multiple co-located IEEE 802.15. 4/ZigBee networks running on adjacent radio channels in industrial environments. IEEE Transactions on Industrial Informatics, 5(2), 157-167.

[11] Chen, F., Talanis, T., German, R., & Dressler, F. (2009, July). Real-time enabled IEEE 802.15. 4 sensor networks in industrial automation. In Industrial Embedded Systems, 2009. SIES'09. IEEE International Symposium on (pp. 136-139). IEEE.

[12] Chen, F., Wang, N., German, R., & Dressler, F. (2010). Simulation study of IEEE 802.15. 4 LR-WPAN for industrial applications. Wireless Communications and Mobile Computing, 10(5), 609-621.

[13] Chen, F., Wang, N., German, R., & Dressler, F. (2008, January). Performance evaluation of IEEE 802.15. 4 LR-WPAN for industrial applications. In Wireless on Demand Network Systems and Services, 2008. WONS 2008. Fifth Annual Conference on (pp. 89-96). IEEE.

[14] Yoo, S. E., Chong, P. K., Kim, D., Doh, Y., Pham, M. L., Choi, E., & Huh, J. (2010). Guaranteeing real-time services for industrial wireless sensor networks with IEEE 802.15.4. IEEE Transactions on Industrial Electronics, 57(11), 3868-3876.

[15] Miorandi, D., & Vitturi, S. (2004, June). Analysis of master-slave protocols for real-time-industrial communications over IEEE802. 11 WLANs. In Industrial Informatics, 2004. INDIN'04. 2004 2nd IEEE International Conference on (pp. 143-148). IEEE.

[16] Vitturi, S., Seno, L., Tramarin, F., & Bertocco, M. (2013). On the rate adaptation techniques of IEEE 802.11 networks for industrial applications. IEEE Transactions on Industrial Informatics, 9(1), 198-208.

[17] Wei, Y. H., Leng, Q., Han, S., Mok, A. K., Zhang, W., & Tomizuka, M. (2013, December). RT-WiFi: Real-time high-speed communication protocol for wireless cyber-physical control applications. In Real-Time Systems Symposium (RTSS), 2013 IEEE 34th (pp. 140-149). IEEE.

[18] Tramarin, F., Vitturi, S., Luvisotto, M., & Zanella, A. (2016). On the use of IEEE 802.11 n for industrial communications. IEEE Transactions on Industrial Informatics, 12(5), 1877-1886

[19] Luvisotto, M., Pang, Z., & Dzung, D. (2017). Ultra high performance wireless control for critical applications: Challenges and directions. IEEE Transactions on Industrial Informatics, 13(3), 1448-1459.

[20] Seijo, Ó., Fernández, Z., Val, I., & López-Fernández, J. A. (2018, June). SHARP: A novel hybrid architecture for industrial wireless sensor and actuator networks. In 2018 14th IEEE International Workshop on Factory Communication Systems (WFCS) (pp. 1-10). IEEE

[21] Schulz, P., Matthe, M., Klessig, H., Simsek, M., Fettweis, G., Ansari, J., & Puschmann, A. (2017). Latency critical IoT applications in 5G: Perspective on the design of radio interface and network architecture. IEEE Communications Magazine, 55(2), 70-78.

[22] Dietrich, S., May, G., Wetter, O., Heeren, H., & Fohler, G. (2017, September). Performance indicators and use case analysis for wireless networks in factory automation. In Emerging Technologies and Factory Automation (ETFA), 2017 22nd IEEE International Conference on (pp. 1-8). IEEE.

[23] P. Bergmans and T. Cover, "Cooperative broadcasting," in *IEEE Transactions on Information Theory*, vol. 20, no. 3, pp. 317-324, May 1974.

[24] D. J. C. MacKay and R. M. Neal, "Near Shannon limit performance of low density parity check codes," in *Electronics Letters*, vol. 32, no. 18, pp. 1645-, 29 Aug. 1996.

[25] L. Michael and D. Gómez-Barquero, "Bit-Interleaved Coded Modulation (BICM) for ATSC 3.0," in *IEEE Transactions on Broadcasting*, vol. 62, no. 1, pp. 181-188, March 2016.

[26] L. Zhang, W. Li, Y. Wu, X. Wang, S.-I. Park, H. M. Kim, J.-Y. Lee, P. Angueira y J. Montalbán, «Layered-Division-Multiplexing: Theory and Practice,» IEEE Transactions on Broadcasting, vol. 62, nº 1, pp. 216-232, 2016.

[27] S. I. Park *et al*., "Low complexity layered division multiplexing system for the next generation terrestrial broadcasting," *2015 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting*, Ghent, 2015, pp. 1-3.

[28] L. Zhang *et al*., "Layered-Division Multiplexing: An Enabling Technology for Multicast/Broadcast Service Delivery in 5G," in *IEEE Communications Magazine*, vol. 56, no. 3, pp. 82-90, MARCH 2018.

[29] J. Montalban *et al*., "Multimedia Multicast Services in 5G Networks: Subgrouping and Non-Orthogonal Multiple Access Techniques," in *IEEE Communications Magazine*, vol. 56, no. 3, pp. 91-95, MARCH 2018.

[30] M. Zhan, Z. Pang, D. Dzung and M. Xiao, "Channel Coding for High Performance Wireless Control in Critical Applications: Survey and Analysis," in *IEEE Access*, vol. 6, pp. 29648-29664, 2018.

[31] IEEE, «Orthogonal frequency division multiplexing (OFDM) PHY specification,» de 802.11 Standard - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Nueva York, Estados Unidos, IEEE Computer Society, 2012, pp. 1583-1630.

[32] Quin, F.; et. Al.; "Effective-SNR estimation for wireless sensor network using Kalman filter"; As Hoc Networks, Elsevier, 2012

[33] A. A. Kumar S., K. Ovsthus and L. M. Kristensen., "An Industrial Perspective on Wireless Sensor Networks — A Survey of Requirements, Protocols, and Challenges," in *IEEE Communications Surveys & Tutorials*, vol. 16, no. 3, pp. 1391-1412, Third Quarter 2014.

[34] A. F. Molisch et al., "IEEE 802.15.4a Channel Model - Final Report," IEEE P802, vol. 15, no. 04, pp. 1–40, 2004.

[35] D. Gómez-Barquero and O. Simeone, "LDM Versus FDM/TDM for Unequal Error Protection in Terrestrial Broadcasting Systems: An Information-Theoretic View," in *IEEE Transactions on Broadcasting*, vol. 61, no. 4, pp. 571-579, Dec. 2015.

[36] Miranda, J., Abrishambaf, R., Gomes, T., Gonçalves, P., Cabral, J., Tavares, A., & Monteiro, J. (2013, July). Path loss exponent analysis in wireless sensor networks: Experimental evaluation. In Industrial Informatics (INDIN), 2013 11th IEEE International Conference on (pp. 54-58). IEEE.

[37] A. Varga R. Hornig "An overview of the Omnet++ simulation environment", *Proc. ICST Simutools*, pp. 60 2008.