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PhD Dissertation

Contributions to the Physical and Media Access Control Layer in Wireless Systems for Factory Automation

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Abstract

Industry 4.0 aims to fully digitize industrial processes, with wireless technologies being one of the enablers for scalable and flexible communications. However, current standards and proprietary solutions must meet the industry's tight requirements for fundamental use cases in Factory Automation, including high reliability, low latencies, and multi-user communications.

Designing techniques that enable real-time and deterministic behavior when transmitting short packets is a key research challenge toward replacing wired fieldbuses with wireless links. Nevertheless, achieving this objective is obstructed by the limits of current proposals, the industrial channel models' properties, and the need for empirical proof to define the use cases.

This thesis aims to provide technical solutions for achieving high efficiency for short packet communications, deterministic behavior, and robustness against channel effects in wireless systems for Factory Automation, particularly in the PHY and MAC layers.

The first contribution is the definition of system parameters and metrics at the PHY layer, which includes a comprehensive analysis of proposed use cases for industrial and Factory Automation and the introduction of the Field of Applications and metrics for evaluating the reliability and latency performance of the Forward Error Correction (FEC). The second contribution proposes an exhaustive taxonomy of

potential FECs for Factory Automation, followed by the selection of four candidates and their analysis through simulations and literature review. Two simulators, a Bit Coded Modulation transceiver and a WLAN-based simulator are developed to evaluate the reliability and latency of the FECs in practical industrial scenarios.

The final contribution proposes optimizations for IEEE 802.11ax for critical industrial communications, particularly for a demanding use case in Smart-warehouses that requires real-time communications with high reliability, latencies close to 1 ms, and a highly dense network. The proposal includes optimizations in the PHY and MAC layers, such as preamble optimization, and two deterministic algorithms for exploiting retransmissions on the frequency domain. The simulations show that this optimization outperforms existing wireless systems for Factory Automation, achieving the proposed system parameters and offering robustness against industrial channels and multi-user communications for the established latency threshold.

Overall, this thesis provides technical solutions for achieving high efficiency, deterministic behavior, and robustness against channel effects in wireless systems for Factory Automation, particularly in the PHY and MAC layers. The proposed optimizations for IEEE 802.11ax offer promising results for critical industrial communications.

Resumen

La industria 4.0 tiene como objetivo digitalizar completamente los procesos industriales, y las tecnologías inalámbricas representan uno de los habilitadores para comunicaciones escalables y flexibles. Sin embargo, los estándares y soluciones propietarias actuales deben cumplir con los estrictos requisitos de la industria en casos de uso fundamentales para la automatización de fábricas, como alta fiabilidad, latencias del orden del milisegundo y comunicaciones multiusuario.

Diseñar técnicas que permitan un comportamiento en tiempo real y determinista al transmitir paquetes cortos es un desafío clave en la investigación para reemplazar los buses de campo con cables por enlaces inalámbricos. Sin embargo, este objetivo se ve obstaculizado por las limitaciones de las propuestas actuales, las propiedades de los modelos de canales industriales y la necesidad de pruebas empíricas para definir los casos de uso.

Esta tesis tiene como objetivo proporcionar soluciones técnicas para lograr una alta eficiencia en las comunicaciones de paquetes cortos, un comportamiento determinista y robustez contra los efectos del canal en los sistemas inalámbricos para la automatización de fábricas, especialmente en las capas PHY y MAC.

La primera contribución es la definición de parámetros y métricas del sistema en la capa PHY, que incluye un análisis exhaustivo de los casos de uso propuestos para la automatización industrial y de

fábricas, la introducción del Campo de Aplicación (definidos en el libro como Field of Application) y métricas para evaluar el rendimiento de fiabilidad y latencia del FEC (Corrección de errores hacia adelante).

La segunda contribución propone una taxonomía exhaustiva de FECs potenciales para la automatización de fábricas, seguida de la selección de cuatro candidatos y su análisis, a través de simulaciones y revisión bibliográfica. Se desarrollan dos simuladores, un transceptor de modulación codificada por bits y un simulador basado en WLAN para evaluar la fiabilidad y la latencia de los FEC en escenarios industriales prácticos.

La última contribución propone optimizaciones para IEEE 802.11ax para comunicaciones industriales críticas, especialmente para un caso de uso exigente en almacenes inteligentes que requiere comunicaciones en tiempo real con alta fiabilidad, latencias cercanas a 1 ms y una red altamente densa. La propuesta incluye optimizaciones en las capas PHY y MAC, como la optimización de la preámbulo y dos algoritmos deterministas para aprovechar las retransmisiones en el dominio de la frecuencia. Las simulaciones muestran que esta optimización supera a los sistemas inalámbricos existentes para la automatización de fábricas, mejorando las prestaciones de los parámetros del sistema propuestos, y ofreciendo robustez frente a canales industriales y comunicaciones multiusuario, para el umbral de latencia establecido.

En resumen, esta tesis proporciona soluciones técnicas para lograr alta eficiencia, comportamiento determinista y robustez frente efectos del canal en sistemas inalámbricos para la automatización de fábricas, especialmente en las capas PHY y MAC. Las optimizaciones propuestas para IEEE 802.11ax ofrecen resultados prometedores para las comunicaciones industriales críticas.

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Chapter 1

Introduction

1.1 Background

The fourth industrial revolution, also called Industry 4.0, is one of the most promising fields where research on information technologies is under development. Its principal goal is to digitalize the entire industrial process. The transition requires the inclusion of the latest communication technologies: wireless networks, tactile internet, Internet of Things, and in general, the optimization of the so-called Cyber-Physical Systems. Wireless communications bring significant advantages to this scenario while posing relevant technological challenges [1]. This transition will take several benefits regarding costs, production, and safety for operators.

Numerous actors from both the industrial world [2–5], as well as from the standardization committees [6–8] have established several guidelines for the successful passage from wired to wireless communications for a variety of scenarios [4]. Indeed, the industrial world encompasses diverse environments that differ in applications and environmental properties. Some examples are factory production processes or FA, surveillance systems, electricity production assets, transport infrastructure, oil production, chemical material handling, etc. FA is among the most challenging use cases for ad-hoc wireless system design and deployment.

Contrary to traditional requirements of generic wireless communications, which entail the transmission of large-size data, FA wireless communications involve the transmission of short data packets with high reliability and reduced latency for a variable number of nodes connected in the industrial network. These communications are necessary for three main fields: monitoring the whole industrial process, controlling the machinery's interactions within the processes, and for safety purposes.

In the last decade, optimized versions of commercial wireless systems such as IEEE 802.11, IEEE 802.15.4, and 5G NR have been proposed to cope with these new applications. Nevertheless, these proposals only partially cope with the requirement for the most critical scenarios. Many aspects affect the desired performance. Among them, the reduced efficiency for short packet transmission and the multipath effect of the industrial environment dramatically affects the desired performance of these systems. Nevertheless, the rising need for real-time communications that emerged in the last ten years has encouraged researchers worldwide to provide efficient solutions for proposing more efficient systems in the next future. The design of deterministic protocols and the development of the coding theory for short packets are part of this evolution.

1.2 Motivations for This Thesis

Factory Automation requires high-performance industrial wireless communications systems. High performance is definable as the need for the simultaneous fulfillment of strict performance for numerous parameters. Nevertheless, the literature highlights three aspects that complicate this challenge.

- Strict system performances for the wireless systems are necessary to automate the factory processes completely [9, 10].
- Lack of validation for the parameters value defined for the use cases. The absence of a standard guideline for the definition of use cases causes discrepancies among the guidelines provided by the different committees and publishers [7, 10].
- The current wireless systems lack in the following aspects.
  - Reduced efficiency for the short-packet domain. Traditionally, wireless systems are proposed for large-packet communications. Therefore, these schemes need some optimizations [4, 11].
  - Deterministic MAC protocols. In commercial wireless systems, the MAC protocols are CSMA based. These protocols aim to avoid collisions among network devices. Indeed, before the data transmission, the devices listen (or check) the channel to detect if other transmissions occupy it. On the one hand, this approach helps prevent data loss due to collisions. Nevertheless, on the other hand, it provides suboptimal latencies for Factory Automation applications [4, 12].
- The industrial channel properties could dramatically affect the overall industrial wireless systems performance [12–14]. A high number of retransmissions could be necessary to face bad channel conditions. Consequently, the more retransmissions are required, the more latency is obtained.

The first motivation for this thesis was to provide alternative methodologies to the current wireless solutions at the PHY layer. Traditionally, these systems adopt classic channel-coding techniques such as Convolutional Codes and Reed-Solomon that, for their simplicity, are adopted to achieve low latency performance at the PHY layer [9]. Traditionally, these techniques are suitable for short-packet communications. Nevertheless, they do not exhibit high decoding performance. The rising interest in URLLC has opened the door to new frontiers for coding theory. New methodologies have been presented during the last ten years, offering valid alternatives to traditional strategies and showing promising performance with reduced complexity. An example is given new LDPC codes, and Polar recently proposed for URLLC applications within 5G NR.

The performance of the modern channel-coding techniques must be evaluated in terms of reliability and latency and compared with the classical approaches.

Another motivation is to suggest high-performing schemes for the wireless standard. The main idea is to offer optimized PHY and MAC layer schemes for critical scenarios, allowing high performance within high-density networks. The current proposals are based on old standards like IEEE 802.11n, which are designed for single-user communications [15–17]. An alternative has been detected in 5G NR, but unfortunately, its structure does not allow extremely low latencies, typically considered equal to or below 1 ms. Nevertheless, modern standards like IEEE 802.11ax or the forthcoming IEEE 802.11be show potential for implementation in these scenarios due to the introduction of OFDMA and the increasing number of data subcarriers. Optimizations of the waveform and the scheduling for IEEE 802.11ax/be will undoubtedly introduce more efficient solutions for these scenarios.

In summary, this thesis aims to consolidate the knowledge and experience earned during the doctoral years and contribute to the advancement of Industry 4.0. Specifically, the research focused on developing more efficient solutions for Factory Automation, particularly for critical scenarios. Indeed, their strict requirements need specific schemes for PHY and MAC layers. On the one hand, the current PHY layers are inefficient for short-packet communications, an essential requirement for achieving this objective. On the other hand, the current deterministic MAC layer protocols are not designed to meet industrial use cases' demanding requirements. The results offered by developing these topics can be valuable for researchers and industry professionals seeking to improve wireless communication systems' performance in Factory Automation environments.

1.3 Objectives

In the last decade, optimized versions of commercial wireless systems, such as IEEE 802.11, IEEE 802.15.4, and 5G NR, have been proposed to address the needs of industrial applications. However, these proposals only partially fulfill the requirements for the most critical scenarios. Many factors affect the desired performance, including reduced efficiency for short packet transmission and the multipath effect of the industrial environment, which significantly impact the performance of these systems.

The main objective of this thesis is to provide ad-hoc PHY and MAC designs that can meet the demanding requirements of critical scenarios in industrial communications. For this goal, several technical objectives are defined:

- **Definition of system performance and metrics for the industrial wireless systesms for Factory Automation.**

  The community provides different use case visions. Therefore, there is no unique direction for defining the parameter values for industrial communication. Another relevant aspect is the lack of metrics for the PHY layer evaluation. Traditionally, the issue is addressed at the MAC layer. Nevertheless, the strict latency requirements in the order of 1 msec combined with high-reliability values below 10^{-6} require further analysis at the PHY layer. Indeed, the last decade introduced new approaches to channel coding toward short packet communications. These methodologies outperform traditional ones, such as Convolutional Codes. For this reason, a methodology for comparing these techniques must be provided, considering the demanding requirements required in many scenarios.

  This analysis requires the following steps.

  - Collection of the guidelines related to the definition of the use case for industrial wireless communications up to date.
  - Search of the main metrics for the analysis of the channel coding (or FEC).

- Characterization of each proposal: target and parameters
- Candidate detection, taking into account their advantages and disadvantages

- **Analysis and proposal of channel coding techniques (FEC) for industrial wireless communications.**

  The requirements for critical scenarios can be met by combining PHY layer techniques with MAC layer techniques. On the PHY side, with more robust Forward Error Coding (FEC) techniques that guarantee high reliability and very low latency, while on the MAC side with retransmission techniques that further increase the reliability performance without drastically worsening the latency. As far as the PHY layer is concerned, a specific solution is given by the Short Packet Coding Theory, whose objective is to propose FEC solutions for the transmission of short information guaranteeing at the same time high reliability and very low latency. This technical objective aims to provide a valid alternative to the channel coding techniques applied within industrial wireless systems. The following steps have been detected for the achievement of this issue.

  - Definition of a taxonomy for channel coding techniques for industrial wireless communications.
  - Analysis of the advantages and disadvantages of each technique.
  - Selection of the candidates.
  - Search of decoding algorithms for candidates suitable for achieving the demanding latency requirements.
  - Design a BCM platform for reliability comparisons
  - Analysis of the candidates' performance in short packet conditions under AWGN.
  - Design an IEEE 802.11 transceiver simulator for comparisons between the proposals and the current solution proposed by these standards.
  - Analysis of the performances with industrial channel models.

- **Analysis and proposals of a deterministic OFDMA technique for industrial wireless systems.**

  OFDMA is one of the candidates detected for critical scenarios, particularly if a high density of interconnected nodes is required. In addition, this technique shows robustness against frequency selective fading, typical for industrial environments. Indeed, it could be operated for communications based on exploiting frequency diversity, which improves the reliability performances for these scenarios. Nevertheless, the current wireless systems are designed for scenarios different than critical industrial scenarios, even for efficient short-packet communications. Following the subsequent steps, this technical objective provides optimized PHY and MAC schemes to improve the OFDMA performance within IEEE 802.11ax.

  – Definition of a use case for Factory Automation.
  – Detection of the use case's issues
  – Description of the proposal that includes network topology, PHY optimizations for IEEE 802.11ax, and MAC alternatives for exploiting frequency diversity for the retransmissions.
  – Development of a toolkit for the simulations.
  – Analysis of the reliability performances.
  – Analysis of the superframe achievable latencies.

1.4 Outline & Contributions

This thesis is composed of six chapters. The first chapter introduces the existing challenges for industrial wireless communications in Factory Automation environments and defines the objectives of this thesis. This work is the result of different publications listed in Chapter 1, Section 5. These contributions compose the thesis's main contents, described from Chapter 2 to Chapter 5. Each chapter proposes different methodologies that are explained in detail. Finally, Chapter 6 offers the conclusions obtained by the research derived from this thesis, highlighting the main contributions and addressing new topics for future research.

The contributions of each Chapter are argumented as follows.

- **Chapter 2:**

  This chapter provides an extensive background analysis of the main topic of this thesis, which are use case vision, industrial wireless systems, FEC techniques, and deterministic MAC techniques. Each proposal is compared to provide the best industrial communications solutions in critical scenarios. These surveys converge in a deep state-of-the-art.

- **Chapter 3:**

  The content of this chapter consists of two main proposals for providing a metric evaluation for industrial communications within factories. Both are based on the state-of-the-art presented in the previous chapter. The first contribution proposes a uniform use case definition for factory applications. In contrast, the second one presents metrics for the PHY layer to compare the FEC techniques.

- **Chapter 4:**

  This chapter aims to propose ad-hoc FEC techniques for industrial wireless systems. The candidates are compared in terms of reliability and latency. The reliability is measured via MATLAB simulations, whereas latency is evaluated via the results encountered in the literature as decoding latency. Decoding latency is the metric detected for the latency in Chapter 3. In addition, a

WLAN transceiver simulator with industrial channel models is proposed for reliability analysis. This analysis allows candidate comparisons with an existing PHY layer model and takes into account the physical properties of the industrial channel models.

- **Chapter 5:**

  This chapter introduces an optimized solution of IEEE 802.11ax for critical scenarios in Factory Automation. The use case proposed is smart warehouses. Indeed, the most critical processes require simultaneously high reliability for numerous interconnected users in extremely low latencies. The chapter provides technical aspects of the PHY and MAC layers proposals. Moreover, the system performance is compared in latency, reliability, and multiuser with previous proposals.

- **Chapter 6:**

  This last chapter summarizes the conclusions from this research experience, emphasizing the main contributions of this thesis and discussing the conclusions obtained. Future research challenges associated with these results are also proposed.

1.5 List of Publications

1.5.1 Publications and Activities Related to this Thesis

International Journals

[J1] L. Fanari et al., "A Survey on FEC Techniques for Industrial Wireless Communications," in IEEE Open Journal of the Industrial Electronics Society, vol. 3, pp. 674-699, 2022, doi: 10.1109/OJIES.-2022.3219607.

[J2] L. Fanari, E. Iradier, I. Bilbao, R. Cabrera, J. Montalban, and P. Angueira, “Comparison between Different Channel Coding Techniques for IEEE 802.11be within Factory Automation Scenarios,” Sensors, vol. 21, no. 21, p. 7209, Oct. 2021, doi: 10.3390/s21217209

[J3]

International Conferences

[C1] L. Fanari, E. Iradier, J. Montalban, P. Angueira, Ó. Seijo and I. Val, "PEG-LDPC Coding for Critical Communications in Factory Automation," 2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Vienna, Austria, 2020, pp. 1135-1138, doi: 10.1109/ETFA46521.2020.9211899.

[C2] L. Fanari, I. Bilbao, R. Cabrera, E. Iradier, J. Montalban and P. Angueira, "Channel Coding for the Control Plane in Broadcast Networks," 2022 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), Bilbao, Spain, 2022, pp. 1-5, doi: 10.1109/BMSB55706.2022.9828789.

[C3] L. Fanari, E. Iradier, J. Montalban, P. Angueira, Ó. Seijo and I. Val, "LDPC Matrix Analysis for Short Packet Transmission in Factory Automation Scenarios," 2020 IEEE International Conference on Electrical Engineering and Photonics (EExPolytech), St. Petersburg, Russia, 2020, pp. 90-93, doi: 10.1109/EExPolytech50912.2020.9243861.

National Research Projects

[P1] Tratamiento de la Señal y Radiocomunicaciones

Funding Institution: Basque Government

Start Date: 1/1/2019

Duaration: 36 months

[P2] Nuevas Tecnologías de Capa Física para Comunicaciones Industriales (PHANTOM)

Funding Institution: Ministry of Economy and Competitiveness. Applied R&D&I Program, Spanish Government.

Start Date: 1/1/2019

Duaration: 36 months

[P3] Tratamiento de la Señal y Radiocomunicaciones

Funding Institution: Basque Government

Start Date: 1/1/2022

Duaration: 48 months

[P4] Técnicas de comunicaciones para la seguridad centrada en el ser humano dentro de entornos industriales (THERESA) // Communications Techniques for Human-Centered Safety in industrial Environments (THERESA)

Funding Institution: Ministry of Economy and Competitiveness. Applied R&D&I Program, Spanish Government.

Start Date: 01/09/2022

Duaration: 36 months

1.5.2 Other Pubblications

Other publications out of the thesis scope have been carried out during the pursuit of this Ph.D.

International Journals

[J1] P. Angueira et al., "A Survey of Physical Layer Techniques for Secure Wireless Communications in Industry," in IEEE Communications Surveys & Tutorials, vol. 24, no. 2, pp. 810-838, Secondquarter 2022, doi: 10.1109/COMST.2022.3148857.

[J2] I. Bilbao, L. Fanari, E. Iradier, P. Angueira and J. Montalban, "Sparse Vector Coding for Short-Packet Transmission on Industrial Communications: Reference Architecture and Design Challenges," in IEEE Open Journal of the Industrial Electronics Society, vol. 4, pp. 1-13, 2023, doi: 10.1109/OJIES.2022.3230142.

[J3] E. Iradier et al., "Analysis of NOMA-Based Retransmission Schemes for Factory Automation Applications," in IEEE Access, vol. 9, pp. 29541-29554, 2021, doi: 10.1109/ACCESS.2021.3059069.

[J4] J. Montalban et al., "Improved Semi-Blind Channel Estimation With Time Domain Cancellation for LDM-LSI," in IEEE Transactions on Broadcasting, vol. 66, no. 3, pp. 613-619, Sept. 2020, doi: 10.1109/TBC.2020.2984995.

[J5] E. Iradier et al., "Using NOMA for Enabling Broadcast/Unicast Convergence in 5G Networks," in IEEE Transactions on Broadcasting, vol. 66, no. 2, pp. 503-514, June 2020, doi: 10.1109/TBC.2020.2981759.

[J6] Iradier, E., Abuin, A., Fanari, L. et al. Throughput, capacity and latency analysis of P-NOMA RRM schemes in 5G URLLC. Multimed Tools Appl 81, 12251–12273 (2022). doi:10.1007/s11042-021-11086-6.

International Conferences

[C1] A. Abuin, E. Iradier, L. Fanari, J. Montalban and P. Angueira, "High Efficiency Wireless-NOMA Solutions for Industry 4.0," 2022 IEEE 18th International Conference on Factory Communication Systems (WFCS), Pavia, Italy, 2022, pp. 1-8, doi:10.1109/WFCS53837.-2022.9779197.

[C2] A. Abuin, E. Iradier, L. Fanari, R. Cabrera, I. Bilbao and J. Montalban, "Non-Orthogonal Multiple Access in 5G from the Energy Efficiency Perspective," 2021 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), Chengdu, China, 2021, pp. 1-6, doi: 10.1109/BMSB53066.2021.9547115.

[C3] E. Iradier et al., "Broadcast/Unicast Convergence in NOMA-based 5G: a RRM Optimization Algorithm," 2020 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), Paris, France, 2020, pp. 1-6, doi: 10.1109/BMSB49480.2020.-9379805.

[C4] E. Iradier, I. Bilbao, G. Pujana, L. Fanari, J. Montalban and P. Angueira, "Multiple Layer P-NOMA in 5G," 2020 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), Paris, France, 2020, pp. 1-6, doi: 10.1109/BMSB49480.2020.-9379385.

[C5] J. Montalban et al., "Design and Performance Analysis of an ATSC 3.0 Model in NS-3," 2020 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), Paris, France, 2020, pp. 1-6, doi: 10.1109/BMSB49480.2020.9379699.

[C6] A. Abuin, E. Iradier, L. Fanari, J. Montalban and P. Angueira, "Complexity Reduction Techniques for NOMA-based RRM Algorithms in 5G Networks," 2020 IEEE International Conference on Electrical Engineering and Photonics (EExPolytech), St. Petersburg, Russia, 2020, pp. 86-89, doi: 10.1109/EExPolytech50912.2020.9243860.

[C7] E. Iradier, J. Montalban, L. Fanari, P. Angueira, O. Seijo and I. Val, "NOMA-based 802.11n for Broadcasting Multimedia Content in Factory Automation Environments," 2019 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), Jeju, Korea (South), 2019, pp. 1-6, doi: 10.1109/BMSB47279.2019.-8971844.

[C8] L. Fanari et al., "Trends and Challenges in Broadcast and Broadband Convergence," 2019 IEEE International Conference on Electrical Engineering and Photonics (EExPolytech), St. Petersburg, Russia, 2019, pp. 153-156, doi: 10.1109/EExPolytech.2019.8906883.

[C9] E. Iradier, J. Montalban, L. Fanari and P. Angueira, "On the

Use of Spatial Diversity under Highly Challenging Channels for Ultra Reliable Communications," 2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Zaragoza, Spain, 2019, pp. 200-207, doi: 10.1109/ETFA.2019.8869055.

Book Chapters

[B1] Webster, J.G., Montalban, J., Iradier, E., Fanari, L. and Siebert, P. (2023). Digital Terrestrial Broadcast Standards. In Wiley Encyclopedia of Electrical and Electronics Engineering, J.G. Webster (Ed.). https://doi.org/10.1002/047134608X.W8420

Chapter 2

A Comprehensive Background of Industrial Wireless Communications for Factory Automation

2.1 Introduction

The chapter aims to provide a detailed background of the topics of this thesis. The result is an extensive survey of industrial communications for Factory Automation. Four topics are included.

The first topic is the analysis of the different KPIs proposed for industrial communications. Indeed, depending on the technical committee, the numerous technical documents and papers provide different visions for the use case definition, which include different KPIs or conflicting values [7, 10]. These visions are collected and compared. The result converges to a state-of-the-art.

The second part reviews the wireless systems considered for Factory Automation applications, categorizing them into three families: IEEE 802, 5G NR, and WirelessHP. A detailed analysis of their PHY and MAC layer architectures is included for each family. In addition, a review of their performance reported in the literature is also included. The performance is defined in terms of latency and reliability.

Then the study moves to more detailed aspects concerning PHY and MAC layer proposals.

A detailed taxonomy of ad-hoc FEC techniques for the PHY layer is proposed, particularly those efficient for short-packet communications. Short-packet is a requirement for many use cases for Factory Automation. After a comprehensive literature review, these methodologies are compared with their reliability and latency performance. The main goal is to provide potential candidates for future proposals for Factory Automation [9]. The reliability study includes the following parameters: the absence of error floors and the achievement of low SNR values with a low error rate, exclusively for short packet communications. Then, the latency analysis mainly focuses on decoding aspects. Low complex architectures and parallel decoding are the elements considered in this case.

Finally, the background study analyzes the MAC layer with state-of-the-art of deterministic techniques for Factory Automation. This family of protocols enables achieving low-latency requirements for various use cases for Factory Automation [10, 18], as the order and timing of data transmissions are predetermined. For this reason, the state-of-the-art comprises this limited category of techniques. The result converges in a taxonomy composed of three families: TDMA, OFDMA, and Multilink Operations. All the proposals are compared regarding reliability, latency, and multi-user capabilities [19].

The chapter concludes with a Summary that contains the main results provided in this survey.

2.2 Requirements, Classifications for Use Cases in Industrial Communications

Throughout the years, numerous actors from both the industrial world [2–5], as well as from the standardization committees [6–8] have established several guidelines for successful wired-to-wireless transition in the numerous verticals or specific application scenarios. These guidelines combine different physical parameters for driving the development of wireless systems within the factories. Due to the absence of a recognized global reference for metrics definition in industrial communications, the parameter values may vary from one publication to another. Common parameters are end-to-end latency, reliability, scalability, range, payload size, jitter, and update rate.

End-to-End latency measures the packet delivery from one node to another in milliseconds. Traditionally it is considered at the Application Layer. Reliability measures the probability of errors occurring during data transmissions. Scalability defines the desired number of nodes within the system. The range represents the maximum communication distance between the nodes and is associated with the environment and the channel model. Payload size is the required dimension for the information, excluding the overhead. Jitter measures the synchronism of communications. Finally, the Update Rate is a metric that forces the wireless system to maintain the sampling rate provided by the network's sensors.

This section provides a state-of-art of these visions, which are also in Table 2.1.

Table 2.1: State-of-the-Art of Guideliness for Factory Automation

Author	Year	Target	Considered Wireless Systems	Metrics	Ref
ISA	2011	Applicative Scenarios for Factory Automation	-	Reliability, latency, and synchronism	[7]
Schulz et al.	2017	Verticals for 5G URLLC	5G URLLC	Latency, reliability, update rate, scalability, range, and device mobility	[8]
Luvisotto et al	2017	Verticals for Industry 4.0	WirelessHP	Reliability, end-to-end latency (goodput in this case), scalability, and range.	[4]
Candell et al	2018	Applicative Scenarios for Manufacturing	-	End-to-end latency, reliability, and scalability	[3]
ETSI	2018	Industrial Verticals and Applicative Scenarios for Manufacturing	-	Reliability, latency, device density, data rate, payload, range, device mobility, and energy efficiency	[7]
NIST	2019	Applicative Scenarios for Factory Workcells	-	Reliability, payload, end-to-end latency, scalability, and update rate	[7]
Sutton et al.	2019	Verticals for 5G URLLC	5G URLLC	Reliability, data size, range, and end-to-end latency	[6]
Cavalcanti et al.	2019	Applicative Scenarios for Factory Automation	IEEE 802.11 ac/ax and forthcoming, 4G LTE and 5G NR	Reliability and latency	[5]

The International Society of Automation (ISA) is a non-profit technical society focusing on Automation. In 2011, this society published the document ISA-TR100.00.03-2011 [7], which provides system requirements for six different classes of use cases for FA. These are grouped in the function of their criticality into three domains: Safety, control, and monitoring. Safety is also a use case class. Control comprises three use case classes for open and closed loop controls. Finally, monitoring corresponds to the use case classes of alerting and logging. The system parameters are reliability, latency, and synchronism at the application layer. Overall, the document does not provide accurate values for the system parameters. For Safety, the guideline does not provide any value for the parameters. The rest of the use cases require a reliability of 10^{-9}, whereas latency and synchronism are demanding for high-criticality scenarios. Nevertheless, the minimum latency considered is 10 ms.

The National Institute of Standards and Technology (NIST) provides different use case classes for a specific environment, the factory work cells [7]. These buildings are considered with typical sizes of 10 m x 10 m. In addition, system parameter values are provided for buildings with maximum sizes of 30 m x 30 m. The classes proposed are five. The first class represents the most critical scenario, Safety. The last class groups the less critical use cases for these environments: monitoring operations. The system performances are considered at the application layer for the following parameters: reliability, payload, end-to-end latency, scalability, and update rate. The document shows specific use cases for a manufacturing scenario where short communication ranges are required. The most critical ones present the following specifications. The reliability is set to 10^{-7}. Latency varies from 0.25 ms to 4 ms. Payload and update are not strictly defined. An extensive range of values characterizes them. Finally, a high density of interconnected devices is not requested for safety and control operations.

Luvisotto et al. [4] illustrate several industrial scenarios defined as requirements for the wireless communication system WirelessHP, conceived by ABB. The verticals are defined in terms of reliability, end-to-end latency (goodput in this case), scalability, and range.

- Process Automation, whose processes involve materials such as oil, gas, metallurgical processes, etc.
- Building Automation describes the control operations within a building. An example is video surveillance services.
- Factory Automation (FA) includes the processes within a production line.
- Power System Automation, which includes the various processes related to electricity production.
- Power Electronics Control which manages the synchronization of power electronics devices.

The document does not provide detailed parameter values for specific environments, as its target is to provide high-performance scenarios or verticals for WirelessHP.

Cavalcanti et al. [5] propose three classes of real-time application scenarios for industry. Soft-Real Time represents scenarios with reduced latency but without other strict requirements. On the contrary, Hard-Real time parameters like synchronization or reliability are also strict. The classes are distinguished by reliability and latency parameters.

Class A includes Soft-Real Time communications required for device interactions and human operators. The authors highlight that current technologies like IEEE 802.11ax/ac and 4G LTE could fulfill the Class requirements. Class B and C comprise Hard-Real Time communications. The author proposes IEEE 802.11ax and 5G NR as candidate technologies for Class B. Finally, Class C is considered for future scenarios that the forthcoming IEEE 802.11be will probably cover.

Sutton et al. [6] propose potential use cases for using 5G URLLC for licensed and unlicensed bands. The proposals are characterized by demanding requirements for reliability and latency. Two industrial scenarios are identified for manufacturing processes: Industrial Automation for control purposes and Process Automation for monitoring and making decisions.

Although the use cases provide a general idea of the required performance, they lack particularity in defining the parameter values. For instance, the parameters proposed are reliability, data size, range, and end-to-end latency, but the range of values for these is wide. Notably, the latency requirements vary significantly between the two industrial scenarios, with Industrial Automation demanding latencies ranging from 0.25 ms to 10 ms, while Process Automation requires latencies between 50 ms and 100 ms.

Schulz et al. [8] focus on providing different use cases detected for latency-critical IoT communications. Among them, also industrial applications are included:

- Factory Automation for device-to-device communications during the manufacturing processes.
- Process Automation for monitoring and diagnosing general industrial processes, like cooling and pumping procedures.
- Smartgrid, which area is extensive.

The main topic of this classification is identified for IoT applications within latency-critical communications. Consequently, the latency is considered for both MAC and PHY layers. The document attempts to provide detailed parameter values for latency, reliability, update rate, scalability, range, and device mobility. Factory Automation presents the most critical requirements as the reliability is set at 10^{-9}. Nevertherless the payload varies from 10 B to 400 B.

The European Telecommunications Standards Institute (ETSI) in [7] provides detailed guidelines for industrial applications. The document proposes six different sections.

- Monitoring & Diagnostic comprises the monitoring of devices without strict latency requirements.
- Discrete Manufacturing that includes the different steps for product production.
- Logistic and Warehouse where described the performances required by vehicles or robots involved within the factories.

- Process Automation, which includes further monitoring applications.
- Augmented Reality that describes the requirements necessary for the interactions between human-computers.
- Functional Safety requires high reliability due to the nature of the processes.

These classifications include reliability, latency, device density, data rate, payload, range, device mobility, and energy efficiency. The most critical scenarios require reliabilities values between 10^{-9} and 10^{-6} for payloads below 300 B.

This section has analyzed the various guidelines for Factory Automation use cases published by technical committees, academic institutions, and vendors. This study highlights that there needs to be a shared vision for the development of these contributions. Indeed, these guidelines show contradictory parameter values when they describe a common application scenario.

2.3 Wireless Sytems and Standards for Industrial Communications within Factories

The literature on wireless communication schemes in FA covers systems based on IEEE 802.11, IEEE 802.15.4, 5G NR, or stand-alone proprietary proposals. Nevertheless, these proposals partially meet the FA requirements as gathered in Table 2.2. This issue will be further discussed in Chapter 3.

2.3.1 IEEE 802 Families

IEEE 802.11 is a family of standards for WLAN communications initially designed to operate in the 5 GHz Industrial Scientific and Medical (ISM) band, specifically with the IEEE 802.11a release. The 2.4 GHz band was included in the IEEE 802.11b/g. The introduction of IEEE 802.11n incorporates the opportunity of switching between these two options. Finally, the recent release of IEEE 802.11ax facilitates the operation in the 6 GHz Band also [16]. One of the main characteristics of the IEEE 802.11 standard family is the lack of determinism in packet arrival times. This aspect prevents their use for real-time communications and, consequently, does not guarantee a controlled latency required in FA use cases. Other negative aspects regard the reliability performances and efficiency of short packet transmissions. Existing systems are far from securing PER values below 10^{-7}.

Traditionally, these standards use OFDM at the PHY layer and are not designed for short packet transmission. Nevertheless, the introduction of OFDMA in IEEE 802.11ax has opened the doors to new application scenarios which require short packet transmissions. Moreover, due to OFDMA, IEEE 802.11ax outperforms the previous IEEE 802.11 versions regarding latency and the number of interconnected users. Further improvements will be appreciated with the introduction of the forthcoming IEEE 802.11be, where extended bandwidth and multi-link communications will be helpful for industrial communications [16].

Regarding the PHY layer design, almost all standard releases use

Orthogonal Frequency Division Multiplexing (OFDM) and FEC techniques. The OFDM waveform has changed with the release of different IEEE 802.11 standards. For example, IEEE 802.11g proposes OFDM spectra in 20 MHz channels composed of 64 subcarriers (52 data carriers). In turn, IEEE 802.11ax has 256 subcarriers available within the same channel width (234 data carriers).

The first IEEE 802.11 standards had FEC modules based on convolutional codes (CC), while more sophisticated algorithms such as LDPC were introduced as an option in the IEEE 802.11n [20]. LDPC has become mandatory for the first time in the standard IEEE 802.11ax. IEEE 802.11ax introduced additional novelties, such as multi-user communications based on OFDMA and a new PPDU design. The new PPDU design introduced in IEEE 802.11ax is nowadays a candidate for the standardization of the upcoming IEEE 802.11be [15]. This standard, also known as Extremely High Throughput, apart from focusing on high data rate profiles, also targets ultra-low latency communications and is, therefore, a good candidate for industrial environments [15].

The worldwide success of the IEEE 802.11 standards has supported various modifications and deterministic MAC approaches over the last decade. These proposals attempt to provide time-aware scheduling by the use of Time Division Multiple Access (TDMA) techniques at the MAC layer, such as RT-WiFi [21], IsoMAC [22], Priority MAC [23] or the recent HAR2D-Fi [24]. Another proposal for FA is SHARP, which attempts to optimize also the PHY of the IEEE 802.11 releases. It proposes the optimization of the PHY of IEEE 802.11g, while at the MAC layer, it proposes a TDMA frame [25, 26]. Recent updates of SHARP are proposed in [17], where OFDMA is introduced to improve the latency performance further.

Another IEEE 802 family considered for industrial environments is the IEEE 802.15.4 standard, which focuses on high-density networks and very short-distance communication ranges. IEEE 802.15.4 was initially sketched for operating in the 2.4 GHz, and 868/916 MHz ISM [27] bands. On the contrary to IEEE 802.11 standards, the IEEE 802.15.4 support deterministic communications. The PHY of 802.15.4 includes Direct Spread Spectrum (DSSS), and Ultra-Wideband (UWB) techniques [28, 29]. UWB combines two modulations known as Burst

Position Modulation (BPM) and Binary Phase-Shift Keying (BPSK). Concerning FEC, IEEE 802.15.4a introduced both CC and RS+CC [30], whereas, in the newest standard IEEE 802.15.4z, only CC [31] has been adopted. Several FA and PA communication systems such as ZigBee, WirelessHART, ISA100.11a, and WIA-FA rely on IEEE 802.15.4 PHY.

2.3.2 5G New Radio

5G New Radio (5G NR) is the Radio Access Network (RAN) standard for the 5G mobile network (including the PHY layer), developed by 3GPP for the 5G mobile network, and it was introduced in 2017 in Rel-15 [32]. 5G NR is the first 3GPP standard targeted for several communication scenarios. Indeed, the previous 3GPP standards only have been developed for broadband communications. One of the covered verticals, the URLLC, was designed to cover verticals requiring real-time applications. Among these, FA is considered one of the most demanding scenarios [33]. 5G NR for covering such verticals includes two operative frequency ranges for short and large-distance communications. The first one, known as FR1, includes 410 MHz - 7.125 GHz, while the second, the FR2, incorporates the frequencies from 24.250 GHz to 52.600 GHz.

The 5G NR PHY layer design partially meets the FA requirements for many applications. Some current limitations are the sub-frame length, which duration currently spans to 1 ms. However, this new standard improves previous releases' robustness with a combination of OFDMA/TDMA MAC techniques and FEC techniques, i.e., LDPC and POLAR. Regarding latency improvement, some new approaches have been recently proposed. For example, in [26], simulations have demonstrated that FDMA provides latency of 1 ms, while in [27], 2-3 ms is achieved.

2.3.3 WirelessHP

WirelessHP is a standalone standard proposal for FA applications based on IEEE 802.11 PHY [11, 34]. Initially, the system only operated in the 5 GHz frequency range [11], while for future work, mmWaves is also being considered, in particular, the 60 GHz license-free band [4].

Regarding the system design, MAC techniques allow for WirelessHP time-aware scheduling and hence the achievement of very low latencies, around 0.5 ms. Nevertheless, considering the reliability, such performance has currently been reached up to PER of 10^{-7} [35]. The adopted FEC are RS, CC, and RS+CC.

Table 2.2: Wireless Systems for Factory Automation

Year	System	PHY Techniques	MAC Techniques	FEC	System Performance		Ref
					E2E Latency [ms]	**PER**	
2004	IEEE 802.15.4a	UWB+FEC, PSSS+FEC, DSSS+FEC	Deterministic	CC, RS+CC	< 3	10^{-7}	[27]
2015	WIA-FA	DSSS+FEC, PHSS+FEC, OFDM+FEC	TDMA	CC, LDPC	8		[4, 36]
2017	5G New Radio	OFDM+FEC	TDMA, OFDMA	LDPC, POLAR	2	10^{-5}	[32, 33, 37, 38]
2017	WirelessHP	OFDM+FEC	TDMA	RS+CC, RS, CC	0.44	10^{-6}	[4, 11, 34]
2018	SHARP	OFDM+FEC, OFDMA+FEC	TDMA, OFDMA	CC	< 30	10^{-7}	[17, 25, 26]
2019	IEEE 802.11ax	OFDM+FEC, OFDMA+FEC	OFDMA	CC, LDPC	10-100	10^{-5}	[20]
2020	IEEE 802.15.4z	UWB+FEC	Deterministic	CC	< 3	$< 10^{-7}$	[31]
TBA	IEEE 802.11be	OFDMA+FEC	OFDMA	LDPC	< 1	$< 10^{-5}$	[16]

2.4 Channel Coding for Industrial Communications

The literature includes many examples of FEC techniques suitable for short packet communication scenarios, and such choices have risen over the years. FEC can be addressed as memory-based and memoryless FEC (or Block Codes). This section aims to provide a state-of-the-art of them, moreover suggesting some FEC candidates for FA wireless systems.

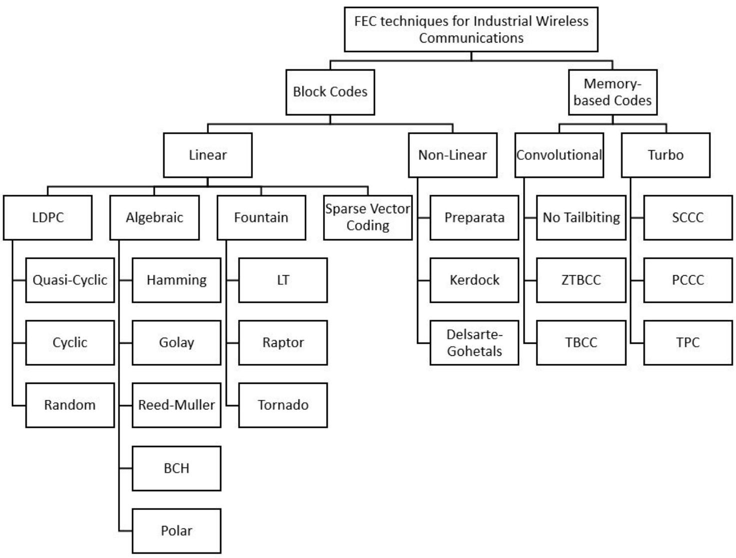


Figure 2.1: A detailed represenation of the FEC techniques adoptable within industrial communications

2.4.1 Block Codes

Block codes are a class of FEC in which the data stream turns into a block of K bits; subsequently, by using a generating matrix, further $N - K$ bits, known as redundancy bits, have been included. The code rate $R = \frac{K}{N}$ specifies the number of these bits.

A primary classification proposed for these techniques consists of distinguishing between linear and non-linear techniques. Linear block codes are less complex than non-linear ones and offer commonly good decoding performances. The non-linear block codes are characterized by a very high complexity that does not allow their consideration in low latency communications nowadays [39]. On the contrary, the respective counterpart shows many applicative examples in numerous standards.

The linear block codes can be classified as a function of the generating matrixes and attainable performance. On this basis, the linear block codes are grouped as follows: LDPC, Algebraic, Fountain, and Compressive Sensing Based. Tables 2.3 and 2.4 compares the block code techniques using reliability in short packet regime and parallel decoding capability. Parallel decoding is a crucial parameter for achieving the stringent latency requirements for FA.

LDPC codes were first introduced by Gallager in the 1960s [40]. Nevertheless, due to their high complexity, they did not gain widespread attention until their rediscovery in the late 1990s by Mackay and Davey [41].The remarkable decoding performance of this family have fostered their use in many standards since the first decade of XXI century. Some examples are IEEE 802.11 [42], WiMax [43], 5G NR [32], ATSC3.0 [44], 10GBase-T [45], WiGig [46], DVB-T2 [47, 48], DVB-S2 [49], and Consultative Committee for Space Data Systems (CCSDS) [50], Generally the LDPC are classifiable into three main subfamilies: Random LDPC [40], Quasi-Cyclic (QC) LDPC [51], and Cyclic LDPC [52], among these QC-LDPC are suitable for communications in FA scenarios; indeed, the possibility of a full parallelization secures low latencies. Nevertheless, QC-LDPC shows error floors in BLER-based analysis [36] in short packet transmissions. This problem can be partially solved by the combination with CRC [53, 54].

Algebraic codes include a wide set of FEC techniques that, due to their mathematical properties, exhibit two main advantages: easy implementation and generally high decoding performance [36]. WPAN [55], DVB-T [56], DVB-T2 [48], IEEE 802.11ad [57], CCSDS [58, 59], MediaFLO [60] and 5G NR [32] are examples of standards that employ this FEC family. Among the several FEC grouped as Algebraic, the authors of the paper have identified four main subfamilies: the Hamming codes [61], Golay codes [62], the BCH codes [63–65] and the Reed-Muller codes [66]. Among the most well known Algebraic techniques, there are Reed-Solomon [67], and Gabidulin [68] that belong to BCH, whereas the Reed-Muller subfamily includes the recently developed Polar codes [69]. Regarding the Algebraic codes in the short packet regime, on the one hand, their decoding performance worsens [36]. On the other hand, the use of parallel decoding is possible [36]. However, a few exceptions, suitable for short packet transmissions, have been introduced recently in the literature, as the cases of Polar codes [70–72], and BCH codes with OSD decoding [73]. A negative aspect concerned OSD decoding is the increased decoding latency [73].

Fountain codes were introduced in the late '90s by Bayers et al. [74] to propose an efficient solution in multicast communications, in particular, to enhance the efficiency of Automatic-Repeat-Request (ARQ) [75]. Indeed standards employed in multicast and broadcast communications, such as 3GPP MBMS [76], and ATSC3.0 [77] use these FECs. The large number of Fountain techniques developed over the years can be categorized into three main sub-families: the LT codes [78], the Raptor codes [79], and the Tornado codes [80, 81]. Fountain codes present a high complexity [82] which prevents their use in URLLC and especially for FA [36]. However, recent versions of Fountain have been proposed for URLLC scenarios, such as in [83] and [84], where the transmission scheme is significantly simplified. The proposed scheme in [84] does not offer error floors for BLER values below 10^{-7}.

Sparse Vector Codes (SVC) are a relatively new class of FEC techniques that have emerged in recent years. They are based on the principles of Compressive Sensing [85], a signal processing technique that can be applied to sparse signals to reduce the data needed for their reconstruction. A few non-zero elements characterize sparse signals, and compressive sensing exploits this sparsity to acquire and represent the signal efficiently. The first studies on SVCs began around 2017, and initial results have shown promising performance for very small block sizes, particularly for values of K below 100 bits. In fact, in these cases, SVCs have been shown to perform comparably to Polar codes, a well-established FEC technique [86–88]. However, the properties related to their generation matrix show worsened decoding performance at high Code Rates ($R \leq \frac{1}{4}$). Furthermore, the required representation of data into sparse vector form limited the use of SVC exclusively to ultra-small K values [86]. Recently, the literature proposed some implementations related to these new techniques. In [89], the computational complexity is estimated, whereas in [90], the implementation results are given in terms of reliability and decoding latency.

Finally, the non-linear block codes are known to offer high decoding performance, but their implementation is typically complex, and costly [91]. The most well-known non-linear codes include the Preparata codes [92], Kerdock codes [93], and Delsarte-Goethals codes [94].

Nevertheless, the recent binarization for Preparata and the Kerdock codes proposed in [39] opens new frontiers for their application within low latency communications.

2.4.2 Memory-based FEC codes

Since the 1960s, Memory-based codes have been applied in numerous systems. The behavior of these techniques is comparable to a state machine, where the data stream passes through different states. Each state is associated with the value of a memory register of the FEC module. A generator polynomial defines the connection between the registers and the relative operations. The encoding process finishes when the last bit of the data stream passes through. It is possible to distinguish two families among the different techniques: Convolutional Codes (CC) and Turbo Codes. Table 2.5 shows a comparison between these techniques by taking into account the reliability performance in short packet regime and the possibility of parallel decoding.

CC codes were introduced by Elias in 1955 [95]. CC consists of the convolution operation between bitstreams containing the data and a bit sequence, resulting from the passage of such data in dedicated shift registers. These later constitute a finite-state machine. Unlike block codes, CC allows faster decoding since the encoding/decoding is enabled after the detection of a bitstream, whereas, in block codes, encoding/decoding requires the entire block bit sequence. Nevertheless, block codes give better decoding performance. Principally for its simplicity, CC has achieved wide success from the sixties; Indeed, several standards, such as IEEE 802.11 [42], DVB-T [56], UMTS [96], LTE [97], CCSDS [59] and the Mars Reconnaissance Orbiter NASA

Table 2.3: Block Codes and FEC Comparison Part I

Typology	Family	Subfamily	Parallel Decoding	High Reliability in Short Packet Transmission	Ref
Linear	LDPC	Cyclic		X	[52]
Linear	LDPC	Quasi-Cyclic	X	X	[51]
Linear	LDPC	Random		X	[40]
Linear	Algebraic	Hamming	X		[61]
Linear	Algebraic	Golay	X		[62]
Linear	Algebraic	Reed-Muller	X		[66]
Linear	Algebraic	BCH	X		[63–65, 67, 68]
Linear	Algebraic	5G-NR	X	X	[69]
Linear	Fountain	LT	X		[78]

Table 2.4: Block Codes and FEC Comparison Part II

Typology	**Family**	**Subfamily**	**Parallel Decoding**	**High Reliability in Short Packet Transmission**	**Ref**
Linear	Fountain	Raptor	X		[79]
Linear	Fountain	Tornado	X		[80, 81]
Linear	Compressive Sensing Based	SVC		X	[86–90]
Non Linear		Preparata		X	[92]
Non Linear		Kerdock		X	[93]
Non Linear		Delsarte-Goethais		X	[94]

Mission [98]utilize CC techniques. There are two main subfamilies of CC: without padding and with padding. CC without padding requires simpler architectures than the counterpart, and, as a consequence, this technique is faster. However, the absence of a padding sequence impacts the decoding performance. Indeed, these techniques provide poor decoding performance during the passage of the first bits of the stream caused by the absence of correlation between the initial and the final state. CC with padding improves the decoding performance by including a known sequence for these states, and consequently, a correlation is provided since the first transmissions. CC with padding can be grouped into Zero Tailbiting Convolutional Codes (ZTBCC) and Tailbiting Convolutional Codes (TBCC) [99]. ZTBCC has padding composed of zero bits, which on the one hand, improves the performance. However, this option affects the effective code rate [100]. In TBCC, the initial and final states of the encoder are identical. However, this strategy increases the decoding performance in short packet regimes at the expense of complexity.

Berrou et al. [101] proposed Turbo codes in 1993, one of the best performing codes up to date. They have been incorporated into many standards since 1990s. Examples are LTE [97], WiMAX [43], MediaFLO [60] and the Mars Reconnaissance Orbiter NASA Mission [98]. Generally, the Turbo codes can be grouped into Parallel Concatenated Convolutional Codes (PCCC), Serial Concatenated Convolutional Codes (SCCC) [101, 102] and Turbo Product Codes (TPC) [103]. PCCC and SCCC present similar performance in terms of complexity and reliability. Comparisons between these two architectures are encountered in both [104] and [105]. [104] shows the better decoding performance of SCCC for BLER below 10^{-6}. In more detail, SCCC achieves the mentioned performance at 7dB, assuming the AWGN channel model. On the contrary, [105] suggests the use of PCCC over SCCC analyzing the results of complexity and reliability, assuming a BLER of 10^{-2}, also in this study, under the AWGN channel. Analyzing the Turbo subfamilies, TPC is considered as the most promising from a theoretical analysis standpoint [36]. However, nowadays, no hardware implementations are found in the literature, despite the presence of parallel decoding scheme proposals [106]. Among the three subfamilies, only PCCC has several hardware implementations with parallel decoding architectures, such as [107] and [108].

2.4.3 Existing FEC schemes within Industrial Wireless Systems

In industrial wireless communications, the use of ad-hoc FEC is necessary for providing highly reliable communications with reduced latencies. Currently, the most popular schemes applied in these environments are based on RS, CC, LDPC, and Polar. Information about their structure and related published research is provided here.

2.4.3.1 WirelessHP RS+CC

Several FEC candidates have been considered for the WirelessHP [36]. Among the alternatives, the RS+CC based on [109, 110] has been adopted for the first laboratory trials focused on the PHY layer [111]. RS is the outer code, while CC is the inner code. There are two main reasons. First, the RS achieves high decoding performance. Second, the concatenation of RS and CC codes allows for high-throughput transmission at reduced decoding latencies due to the efficient Viterbi decoding algorithm.

The FEC performance was evaluated for different configurations. Two different code lengths were considered for the RS code: 15 bits and 31 bits. The first was used for data sizes between 9 and 13 bits, while the second covered data sizes between 19 and 29 bits. The following code rates were used for the outer code (CC): 5/6, 3/4, and 2/3.

In [111], these configurations have been adopted for the data transmission between two nodes implemented with two Universal Software Radio Peripherals (USRP), considering a bandwidth of 5MHz. The better performances have been obtained considering CC (2/3), where low values of PER (below 10^{-7}) were obtained assuming periods for the packet transmissions less than 100 μs.

Table 2.5: Memory Codes and FEC comparison

Family	Subfamily	Parallel Decoding	High Reliability in Short Packet Transmission	Ref
Turbo	SCCC		X	[101, 102]
Turbo	PCCC	X	X	[101, 102]
Turbo	TPC		X	[103]
Convolutional	No Tailbiting	X		[95]
Convolutional	ZTBCC	X		[99]
Convolutional	TBCC	X	X	[100]

2.4.3.2 IEEE 802.11 CC

The IEEE 802.11 CC is ZTBCC and is based on [112]. A tail bit sequence of 6 bits set at zero is included in the data block before the encoder and is used to improve the decoding performance. The Convolutional Encoder is designed for offering a default code rate of 1/2. For multiple code rate choices, puncturing is applied after encoding. Two different puncturing modes are included. The first allows $1/2 < R < 5/6$, while the other is used for R=5/6. The use of the Viterbi decoding algorithm allows extremely-reduced decoding latencies.

[26] shows the results of SHARP obtained by OMNET++ simulations. These results show that, without the use of retransmissions, IEEE 802.11 CC helps in the obtainment of PER values less than 10^{-6} for latencies close to $500\mu\ s$.

2.4.3.3 5G NR CA-Polar

5G NR CA-Polar are used within the 5G NR control channel due to the high decoding performance for short packets. Such performances are improved for coupling the CRC sequence with the information block at the PHY layer. This approach is twofold. First, they are used for improving the error detection performance. Second, their combination with the SCL decoding algorithm also allows error correction [113].

Multiple data size and code rates are available with 5G NR Polar. Data range from 30 to a maximum of 1024 bits. At the same time, the code rate could vary from 1/5 to 5/6 due to the use of the following rate matching operations: puncturing, shortening, or repetition.

In [114], which analyzes FEC techniques for Factory Automation, shows that CA-Polar outperforms the IEEE 802.11 CC for data with reduced sizes (in the order of 100 bit) if combined with SCL. In this case, decoding latencies are below 1 μs, as the parallelization could be applied to this algorithm. Further SCL decoding proposals based on partial parallelization are proposed in [115].

2.4.3.4 5G NR LDPC

5G NR QC LDPC codes are used for the data transmission and are designed to be applied for many scenarios. Among these, also FA is included. Many advantages are associated with this technique. First, the error floors are detectable for PER values below 10^{-5} for a large set of code rates. Second, reduced decoding latencies due to the high degree of parallelism. The reliability performance is improved for using CRC as outer code, while the block segmentation before the encoding allows significantly reduced latency performances [113].

5G NR QC LDPC offers many data sizes, which vary from less than 100 to 8448 bit. Two base matrices (BM) are proposed. BM1 is usually applied with large data, while on the contrary is used BM2. Puncturing and shortening are applied to achieve code rate flexibility, varying from 19/20 to 1/5.

In [18] it is shown that due to the parallel decoding, 5G NR QC LDPC could achieve decoding latencies below 1 μs for achieving PER values below than 10^{-5}.

2.5 Access Techniques for Industrial Wireless Communications

Industrial wireless communication must provide demanding physical requirements for several factory processes, particularly for those involved in manufacturing. Nevertheless, this challenge is complicated by the following reasons.

- Demanding KPIs values. Simultaneously providing short payloads, high reliability, and reduced latency is hard to achieve.
- The current wireless systems present limits for fulfilling the most demanding use cases. On the one hand, they do not provide high efficiency for short-packet communications. On the other hand, they are not designed to provide high-density multi-user communications with latencies close to 1 msec.
- The Industrial Channel Models proposed in the literature show a typical behavior concerning high coherence times and frequency selective fading. These effects could obstruct the desired reliability as highlighted in previous works as [12, 14]. As a consequence, the latency is also affected.

A break-even point is the use of deterministic MAC layer approaches instead of the CSMA one, traditionally included in the IEEE 802 standards [4,9,10]. These methodologies are classifiable into three main groups TDMA, OFDMA, and Multilink operations (depicted in Figure 2.2).

This section presents an updated overview of state-of-the-art methodologies in wireless communication systems. Table 2.6 compares these proposals based on their reliability, latency, and multi-user capabilities. Reliability is closely associated with diversity, which determines the retransmission domain in either time or frequency. Multi-user capability indicates the maximum number of interconnected nodes that a superframe can accommodate. To evaluate latency performance has been considered 1 ms as the reference latency requirement. This value is the threshold considered in the scenarios investigated in this thesis.

Table 2.6: State-of-the-Art of MAC proposals for industrial communications within factories

Author	Year	Proposal	Standard	MAC Layer	Diversity	Multiuser	Latency	Ref
Seijo et al.	2018	SHARP	IEEE 802.11g/n	TDMA	Time based	20	LOW	[25, 26]
Sachs et al.	2018	Optimized MAC Layer for URLLC	5G NR	TDMA	Time based	-	MEDIUM	[37]
Bankov et al.	2018	ax-SRPT	IEEE 802.11ax	OFDMA	Resource Allocation	20	HIGH	[116]
Costa et al.	2019	RT-Wifi	IEEE 802.11	TDMA	Time based	Maximum 80 users	MEDIUM	[21]
Lopez-Perez et al.	2019	Legacy	IEEE 802.11ax/be	OFDMA	-	512	HIGH	[15]
Seijo et al.	2020	w-SHARP	IEEE 802.11g/n	OFDMA	-	50	LOW	[17]
Aijaz	2020	Virtual TDMA	IEEE 802.11ax/be	OFDMA	Multi-AP	100	HIGH	[24]
Filoso et al.	2020	Closed-Loop Feedback Controller	IEEE 802.11ax	OFDMA	Resource Reallocation	25	HIGH	[117]
Tutelian et al.	2021	Resource Reallocation against Frequency Selective Fading	IEEE 802.11ax	OFDMA	Resource Allocation and Power Management	80	HIGH	[118]
Perez-Ramirez et al	2022	Deterministic MLO	IEEE 802.11be	MLO	Multi-band	-	-	[19]

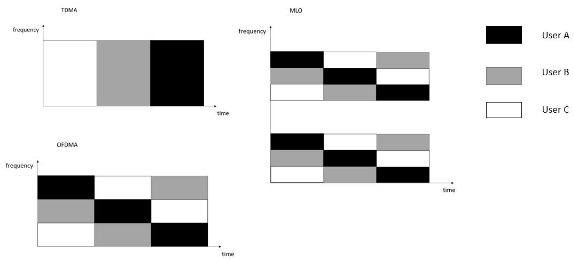


Figure 2.2: Different MAC approaches for Industrial Communications within Factories

Then, latency can be classified as high if it exceeds 1 ms, medium if it is equal to or greater than 1 ms, and low if it is below 1 ms.

2.5.1 TDMA

TDMA is a medium access technique that allocates specific time slots for each user to access the channel, operating solely in the time domain. The main advantages of TDMA are reduced complexity and their deterministic nature, allowing low latencies and synchronism during communications. Nevertheless, these approaches do not provide robustness against the industrial channel properties in certain conditions, as the retransmissions do not consider frequency diversity.

Seijo et al. proposed SHARP [25,26], an optimized version of IEEE 802.11g/n. This proposal presents a solution for industrial use cases with demanding latency, reliability, and synchronism performance. These improvements are obtained by replacing the standard CSMA/CA, typical of the IEEE 802.11 standards, with TDMA when real-time communications are required. In [26], the authors analyze the reliability and latency of the SHARP superframe for different MCS configurations and show that latencies below 1 ms with a PER of 10^{-8} can be achieved, making it suitable for many use cases in Factory Automation.

Sachs et al. [37] proposed an optimized TDMA MAC layer for 5G NR, attempting to introduce this technology for URLLC for latencies of 1 ms. This work analyzes the latency issues of 4G LTE and 5G NR. The proposal introduces the concept of mini-slots for 5G NR, which dramatically reduces the latency performance. Nevertheless, this work does not consider industrial channel models for the analysis.

Costa et al. [21] proposed RT-WIFI for IEEE 802.11, which aims to cope with requirements between RT and non-RT communications in industrial environments. Retransmission periods for reliability improvement are also included. Nevertheless, the latency is higher than 1 ms, critical for many manufacturing processes, and the analysis does not include industrial channel models.

2.5.2 OFDMA

OFDMA is a multiuser communications methodology that consists of subgrouping an OFDM channel into different subchannels or RUs. Traditionally this technique is used in broadband communications standards like 5G NR and 4G LTE. However, also WLAN from IEEE 802.11ax includes this technique. The reason is associated with the rising need for real-time and multiuser communications demanded by technological trends. Also, industrial communications are included.

This approach could address issues associated with latency, reliability, and multiuser. OFDMA is adaptable for deterministic communications, as proposed in [17]. Frequency diversity could be exploited for retransmission purposes, outperforming TDMA.

Bankov et al. [116] propose ax-SRPT, which is based on the scheduler adopted in 4G LTE. This proposal is a solution against the Uplink latency performance of the IEEE 802.11ax. The scheduler organizes the subgrouping based on the data length required by each node for the transmission. This approach is available for networks composed of 60 nodes. Nevertheless, on the one hand, the provided latency is higher for critical scenarios. On the other, no retransmission mechanisms are described.

Lopez-Perez et al. [15] compare the OFDMA performances of both IEEE 802.11ax and IEEE 802.11be, simulating an industrial scenario. The legacy IEEE 802.11ax is considered in this study, and for its complexity, it is not directly applicable to critical use cases. Nevertheless, it could be optimized for these performances. One obstructive element is the trigger frame, introduced by the standard for scheduling downlink and uplink communications. Due to the multitude of QoS required by the standard, its dimension is higher than the data transmitted in many critical scenarios.

Filoso et al. [117] introduce an uplink scheduler for IEEE 802.11ax to improve its subchannels assignation efficiency. This scheduler is based on a closed-loop feedback controller, which organizes the assignations based on the data size and the QoS required by each node in the uplink. The definition of priority levels distinguishes the different QoS from 1 to 5. No retransmission schemes are defined in this proposal. Moreover, the latency required for an uplink period that comprises 25 nodes is higher than 1 ms.

Seijo et al. [17] propose w-SHARP for IEEE 802.11g/n for FA applications, where a deterministic MAC layer OFDMA based is presented. The results show lower latencies compared with a superframe IEEE 802.11ax based. Nevertheless, the benefits of frequency retransmissions are not analyzed.

Aijaz [24] describes VIRTUAL TDMA, which provides deterministic communications for the IEEE 802.11ax OFDMA. This proposal includes a secondary AP to improve efficiency in industrial scenarios. Nevertheless, the obtained latency is above 5 ms.

Tutelian et al. [118] provide a robust solution against frequency selective fading based on IEEE 802.11ax OFDMA. The proposed scheduler organizes the resource reallocation and controls the nodes' transmission power to face the Frequency-Selective Fading effects. Nevertheless, this scheme does not address critical industrial scenarios as it requires high time for the channel estimation.

2.5.3 Multilink Operations

Multilink-operations is a proposal for the forthcoming IEEE 802.11be for highly efficient usage of the spectrum resources in order to meet requirements like high-throughput and ultra-low latency for a multitude of services. The concept is to parallelize the data transmission using different bands simultaneously to improve transmission efficiency.

Perez-Ramirez et al. [19] propose a deterministic approach for multi-link operations for IEEE 802.11be within Factory environments. Nevertheless, this preliminary study does not provide relevant results.

2.6 Summary

This chapter provides an extensive background analysis of the topics developed in the following chapters. The conclusions are the following.

First, there are multiple opinions regarding establishing the system parameters for the use cases for industrial communications. The analysis, in particular, focused on the vertical of Factory Automation. Indeed, the multiple technical documents considered could be distinguished for different system parameters and incoherence for the values proposed.

Second, the wireless system proposals fulfill a limited group of use cases for Factory Automation. Hardware and TDMA methodologies limit the desired performance, particularly reliability and multi-user capabilities.

Then, a comprehensive taxonomy for short packet communications in Factory Automation is presented. This classification includes well-known codes in Factory Automation, alternatives discovered from other applications, and novelties.

Finally, the last part analyzes and compares three families of deterministic MAC layers for Factory Automation: TDMA, OFDMA, and Multilink Operations. In particular, new proposals for systems based on OFDMA and Multilink Operations seem promising for facing the required performance of the most demanding use cases in the immediate future.

Chapter 3

Metrics and Domains for Factory Automation

3.1 Introduction

This Chapter provides two typologies of technical guidelines. The first, defined as Fields of Application, is associated with describing the use cases for Factory Automation. The second includes metrics for the reliability and latency performance for evaluating the FEC techniques in industrial environments.

3.2 Fields of Application Proposal for Factory Automation

This section presents a framework for Factory Automation use cases delineating three distinct domains, defined as Fields of Application. This results from a comparative analysis of various guidelines for determining use cases in this application. The reason is to provide a more comprehensive and unified approach to Factory Automation use cases by reconciling different perspectives. In addition, a comparative analysis of the wireless systems introduced in Chapter 2 is also provided. This study compares the achieved performance with the performance required by the Fields of Application and will be presented in the concluding part of this Section.

3.2.1 Comparisons among the Published Guidelines

Industry 4.0 aims to automate manufacturing processes within factories fully. One of the key goals for achieving this is to substitute cabled communications with emerging wireless technologies such as IoT, Cyber-Physical Systems, and Tactile Internet [1]. Different manufacturing areas may require different devices to control and monitor production, so the network design must consider these specific requirements.

Over the years, various organizations and committees have proposed guidelines for wireless transition in Factory Automation. However, the proposals have been found lacking in certain aspects:

- Some guidelines propose system parameter values that are difficult to justify through empirical studies, such as the reliability values set at 10^{-9} for discrete manufacturing in the ETSI guidelines and for monitoring applications in the Candell et al. guidelines [7].
- The validity of some guidelines is limited to specific environments or buildings. Consequently, these are not applicable to the entire Factory Automation use cases. These guidelines propose

Table 3.1: Comparisons among guidelines

Candidate	Lack of Empircal Studies associated to the parameters value	The target is the totality of Factory Automation process	Includes new applications
ISA	Yes	Yes	No
Candell et al.	Yes	Yes	No
ETSI	Yes	Yes	Yes
NIST	No	No	No
Cavalcanti et al.	Yes	Yes	Yes

metrics associated with environment characterization, such as communication range [3, 7].

- New emerging applications, such as AGVs for logistic purposes in smart warehouses, are not considered in traditional guidelines. These guidelines propose metrics like latency, reliability, payload size, communication range, and synchronism. However, newer applications require additional metrics like device mobility, energy efficiency, and throughput, most of which are not covered in traditional guidelines [5, 7].

Table 3.1 compares the analyzed guidelines in terms of their suitability for addressing the challenges of wireless transition in Factory Automation.

The ISA guidelines [7], being the oldest, do not account for recent technological trends in Factory Automation. Moreover, they lack empirical studies to justify the values defined for the parameters.

The guidelines proposed by Candell et al. [3] share similar properties. Although the guidelines established by ETSI include emerging technological trends for their use cases, some of the metrics seem unjustified, and some of the guidelines are overly detailed.

The NIST guidelines focus on a specific scenario for Factory Automation [7], namely the processes involved within workcells, and the proposed values are based on empirical studies. However, the proposed classification does not include future applications for the studied scenario.

Finally, Cavalcanti et al. [5] offer use cases based on different real-time domains. However, the proposed values are too demanding compared to those in [7], such as the reliability values established for discrete manufacturing, which are set at 10^{-9}, or the latency values provided for monitoring, which include values from 20 ms.

One conclusion from this analysis is that establishing guidelines for Factory Automation requires consideration of two essential elements.

First, Factory Automation encompasses various fields of application that are vital for monitoring and controlling industrial processes' numerous tasks. These fields can be classified as critical and non-critical processes. Their criticality level determines the necessary adaptations to several layers of the Open Systems Interconnection model (OSI model) [119]. Second, each Factory Automation environment exhibits unique characteristics influenced by materials, machinery, density, and building sizes. Specific wireless systems must be designed to fulfill particular conditions for each environment.

For instance, wireless systems suitable for the production stage differ from those suitable for storage, considering the different environments. Factors such as building size are crucial in selecting wireless systems. For example, IEEE 802.15.4 for short distances (about 10m) may be suitable for smaller buildings, while IEEE 802.11 may be ideal for more extensive scenarios. However, despite the varying requirements, certain parameters remain similar across different processes, as highlighted in [5, 7].

This introductory subsection sets the groundwork for further describing the Fields of Application, enabling the subgrouping of use cases for Factory Automation.

3.2.2 Fields of Applications

The wireless systems for Factory Automation are designed for monitoring or controlling the different processes which are required for production or storage.

Monitoring defines communications for transmitting periodic reports. These are by the sensing process of the sensors incorporated in an environment. These messages are fundamental for process diagnosis and preventing any risk.

Table 3.2: Proposed Fields of Application

Fields of Applications	**Reliability** [PER]	**Latency** [ms]	**Payload** [B]
Safety Communications	10^{-9}	0.25-4	From 6 to 24
Critical Communications	$\leq 10^{-6}$	0.5-20	From 8 to 1024
Non Critical Communications	$\geq 10^{-6}$	Not Relevant	Up to 33k

Controlling includes a wide range of applications that are critical for nature. This category must provide control and synchronization of the communications among various devices and machinery involved in production and storage. The main challenge that characterizes these communications is preventing any undesired interruption of the processes.

Table 3.2 presents a classification of the fields of application for industrial wireless systems as a function of the link-level requirements, offering common parameters for classifying the numerous use cases into the field of applications. Three key parameters have been considered: payload length, reliability, and latency. These values provide generic values for the fields of application, which comprise several use cases. Other parameters, such as communication range, are fundamental for defining use cases. Reliability and latency are defined as Packet Error Rate (PER) and End-to-End (E2E) latency. The PER evaluates the correct message interpretation, while the E2E latency estimates the time interval between the data generation and its future reception at the MAC layer.

Based on the presented parameters, three prominent fields of application are recognized: Non-Critical Communications, which include, for example, monitoring operations and involve less stringent requirements. Existing wireless technologies are currently applied in such scenarios. Critical Communications demand communication systems to protect and control machinery and production processes or the movement of AGVs or similar devices. Such scenarios denote strict reliability and latency requirements. Finally, the case of Safety Communications covers all the risk reduction operations associated with personnel and equipment damage prevention and protection. In this case, the communications require extremely low latency data transfer. Generally, in industrial communications and FA, a system is considered safety if it provides only one communication failure during thousand years [7]. This assumption is based on the recommendation IEC 61784, where the communication failure should compose at most 1% of the Mean time to failure, in this case of thousand years [120].

3.2.3 Availability of Industrial Wireless Systems within Factory Automation

Different industrial wireless systems have been proposed for Factory Automation in the last decade. Table 3.3 compares the performance of the industrial wireless systems with the Fields of Applications. The candidates are taken from Table 2.2, only IEEE 802.11be is excluded, as it is still in the standardization process. This study only considers reliability and latency as terms for the comparisons, neglecting other metrics such as the number of connected devices or communication range, which are other demanding parameters in these environments. Also, the availability for short packet communications is included in this discussion as beneficial for achieving high reliability for low latencies [9]. A preliminary observation derived by Table 3.3, is that these proposals are far from fulfilling the totality of use cases for Factory Automation. Observing the performance of WirelessHP, which provides the best performance, is possible recognize that they not fullfill the whole range of values established for Safety Communications. Indeed, WirelessHP could provide an error rate of 10^{-7} in $0.5ms$ [11, 34], which is distant from 10^{-9} in $0.25ms$, the most demanding scenario for safety.

Nevertheless, both WirelessHP, SHARP [25, 121, 122] and IEEE 802.15.4z [35] could be applied for the majority of Critical Communications. On the contrary, 5G NR and IEEE 802.11ax, due to their large waveforms do not cover the whole values range of this field, as their reliability is slightly out of range and the minimum obtainable latencies are 3 ms and 10 ms for 5G NR and IEEE 802.11ax [16] respectively.

Finally regarding Non Critical Communications, the absence of demanding latency requirements allow to suggest the totality of the proposed systems.

In conclusion, the most demanding use cases for Critical and Safety Communications still need to be fulfilled, as highlighted in this discussion.

Table 3.3: Comparison between wireless systems performance and Fields of Applications

System	Year	Reliability	Latency	Short Packet Comm.	Safety	Critical	Non Critical
WIA-FA	2015	-	8	NO	NO	NO	YES
5G NR	2017	10^{-5}	2	YES	NO	LIMITED	YES
WirelessHP	2017	10^{-7}	0.5	YES	LIMITED	YES	OUT OF SCOPE
SHARP	2018	10^{-7}	1	YES	LIMITED	YES	YES
IEEE 802.11ax	2019	10^{-5}	10-100	YES	NO	LIMITED	YES
IEEE 802.15.4z	2020	10^{-7}	3	NO	NO	YES	YES

3.3 FEC Metrics for Industrial Wireless Systems

Numerous Factory Automation use cases, such as control of manufacturing processes and safety systems, require high performance in terms of latency and reliability. These processes need to exchange information in the form of short packets to allow real-time communications. The PHY layer is critical in achieving this goal. A significant role is given to the FEC techniques. Evaluating the accuracy of these techniques, especially in terms of reliability and latency, is crucial to ensure that wireless systems achieve the desired performance. Nevertheless, while the use case requirements are typically proposed at the MAC layer, FECs are traditionally implemented at the PHY layer.

For this reason, this section introduces two metrics for evaluating the PHY layer for Factory Automation applications. These estimate the FEC techniques' performance in terms of reliability and latency. The aim is to determine the best-suited FEC techniques for Factory Automation applications, ensuring optimal system performance for modern manufacturing processes.

3.3.1 Why FEC?

Optimizing all ISO/OSI layers towards real-time communications [119] is necessary for the demanded performance for FA fields of application. Focusing on the PHY layer, two strategies can be considered [111]. First, the Automatic Repeat Request techniques, which are implemented at the MAC layer, introduce some check-bits in the transmitted packet for retransmitting the erroneous messages. However, these retransmissions introduce undesirable delay during the packet transmission [123]. The other strategy is the use of FECs at the PHY layer. These techniques include some redundancy bits within the packet during transmission. At the receiver, this redundancy allows the detection and error correction of the received message, avoiding the delay effect discussed in the previous case.

Consequently, including FEC techniques within industrial wireless systems has potential benefits for achieving the desired performance in terms of reliability and latency. The requirements have been briefly introduced in Section 2.

3.3.2 A background of FEC: From classic to short packet communications

In 1948, Claude Shannon demonstrated that it is possible to achieve error-free data transmission in communication channels affected by noise [124]. This reliability can be accomplished by transmitting data with a code rate R lower than the channel capacity, also known as the Shannon Limit.

FEC techniques are commonly used to implement this approach. They add redundancy to the data transmitted through the communication channel. The magnitude of the redundancy is given by the code rate R. This is calculated as the ratio between the original data size of K bits and the transmitted data size of N bits. Therefore, N must contain a certain redundancy (indeed $N > K$) which helps the receiver detect and correct some of the corrupted bits within the transmitted data, thereby increasing the reliability of the transmission.

While analyzing the performance of FEC techniques is relatively straightforward for large packets, where the Shannon Limit tends to infinity [125], on the contrary, for short-packet communications, additional assumptions are required.

Short packets can be defined as metadata blocks whose dimensions are similar to or less than the preamble adopted by wireless systems for transmitting data between nodes. Another element helpful for its definition is that the signal length of the short packets is much smaller than the coherence time values typically adopted in the Rayleigh Channel models [126]. Moreover, [126] defines theoretical boundaries for evaluating FEC in short-packet communications was proposed. This work highlights that additional metrics are required for evaluating the FECs in the short packet domain. Indeed, in this case, traditional methodologies are not accurate in the code rate estimation of these techniques. Parameters like the channel's coherence time affect this analysis.

Numerous publications have analyzed the use of FEC for short packet communications in recent years.

Sybis et al. [127] compares different FEC candidates for 5G URLLC communications, previously identified by 3GPP. Analysis for both reliability and complexity are proposed, considering different decoding algorithms. Liva et al. [128] presents a survey of modern codes for short packet transmission. Iscan et al. [129] compares different FEC schemes for 5G URLLC communications. Moreover, different decoding algorithms are included in the study. Wu et al. [130] for short packet communications made with SDR, analyzes different FEC candidates. Tzimpragos et al. [131] reviews different FEC schemes for 100-Gb/s optical networks. Also, an analysis of the published results is included. Shirvanimoghaddam et al. [132] reviews the state of the art of the FEC techniques for URLLC. Moreover, a comparison of reliability and decoding complexity analyzes different decoding algorithms. The results are obtained from MATLAB simulations. Qiao et al. [133] compares the performance of numerous FEC within a flexible ASIP decoder. Zhan et al. [36] analyzes FEC candidates for WirelessHP. This work also offers future directions for designing FEC schemes for industrial control applications. Hajiyat et al. [134] compares different candidates for 5G machine-type communications. Shao et al. [115] analyses the published results of the ASIC implementations of different 3GPP FEC techniques. Ahmed et al. [135] in their survey focused on addressing the design for future ARQ schemes, reviews suitable FEC techniques. In [136], Habib et al. study different decoding algorithms for LDPC un the context of Reinforce Learning. Lian et al. compare different decoding algorithms for TBCC and Polar in terms of reliability and complexity [137]. Ferraz et al. [138] analyze and compare numerous decoding algorithms for LDPC addressing issues associated with high-throughput and low energy consumption.

Table 3.4 and 3.5 outlines the contributions of these works, highlighting the lack of pubblications associated to Factory Automation

In conclusion, FEC techniques are crucial for reliable communication in noisy channels, particularly in real-time use cases. Indeed, the noisy channels characterize the Factory Automation environment. Nevertheless, the lack of analysis methodologies associated with FEC for short packets paves the way for new research applied to this regime.

Table 3.4: Surveys regarding FEC for short packet communications Part 1

Author	Year	Proposed Scenario	FEC Survey	Decoding Survey	Hardware Analysis	Reliability Comparisons	Decoding Latency Comparisons	Future Challenges for FEC	Future Challenges for Decoding	Ref
Sybis	2016	URLLC	Yes	Yes	No	Yes	No	No	No	[127]
Liva	2016	Theoretical	Yes	No	No	Yes	No	No	No	[128]
Iscan	2016	Theoretical	Yes	Yes	No	Yes	No	No	No	[129]
Wu	2016	High-Throughput Communications	Yes	Yes	Yes	Yes	No	No	No	[139]
Tzimpragos	2016	Optical Networks	Yes	No	No	Yes	No	Yes	No	[131]
Shirvani-moghaddam	2018	URLLC	Yes	Yes	No	No	No	Yes	Yes	[132]
Qiao	2018	High-Throughput Communications	Yes	Yes	Yes	Yes	No	No	No	[133]
Zhan	2018	High-Throughput Communications for FA	Yes	Yes	No	Yes	No	Yes	No	[36]

Table 3.5: Surveys regarding FEC for short packet communications Part 2

Author	Year	Proposed Scenario	FEC Survey	Decoding Survey	Hardware Analysis	Reliability Comparisons	Decoding Latency Comparisons	Future Challenges for FEC	Future Challenges for Decoding	Ref
Hajyiat	2019	Machine-type communications	Yes	Yes	No	Yes	No	No	No	[134]
Shao	2019	Broadband Communications	Yes	Yes	Yes	No	No	No	Yes	[115]
Ahmed	2021	URLLC	Yes	No	No	No	No	No	No	[135]
Habib	2021	Reinforced Learning	No	Yes	No	Yes	No	No	No	[136]
Lian	2021	Theoretical	No	Yes	No	Yes	No	No	No	[137]
Ferraz	2021	High-Throughput Communica-tions	Yes	Yes	Yes	Yes	No	No	Yes	[138]

3.3.3 Metrics for Reliability

Industrial wireless systems require high reliability during the transmission of short data. A transmission failure could affect critical aspects of the manufacturing processes associated with safety, equipment, and machinery integrity. The error rate is a metric strictly related to the probability of transmission failure. Its measurement in these particular environments is defined at PHY or MAC layers and offers the rate of successfully delivered bits or packets.

A communication failure is caused when the receiver lacks the correct packet reception, and this depends on one of the three following events:

- The receiver does not receive the packet.
- The received packet contains erroneous bits.
- The packet is received outside the latency requirement.

As discussed in Section 3.2, the error rate typically varies from 10^{-9} to 10^{-6} for Factory Automation use cases. The value choice depends on the level of risk associated with the specific use case. However, the error rate for these applications commonly refers to the MAC layer. One reason is the need for deterministic MAC layers [9, 10, 12, 13, 122], which allow the frame retransmission to enhance reliability performance with controlled latencies. Nevertheless, these guidelines can complicate the system design of wireless systems for Factory Automation. On the one hand, the study of new FEC schemes is needed for Factory Automation [9, 11, 36]. On the other hand, current wireless systems only partially meet the requirements of demanding use cases such as safety.

The error rate metrics described in this section are used to evaluate the industrial wireless systems performance, where the desired performances are achievable using FEC and retransmission techniques. Some examples are Bit Error Rate (BER), Block Error Rate (BLER), Packet Error Rate (PER), Packet Loss Rate (PLR), and Connection Error Rate (CER). The terms BLER, PER, and PLR are interchangeable in these scenarios. Commonly, BLER is associated with 5G NR, while PER for

IEEE 802 standards for both PHY and MAC layer. PLR only refers to MAC-layer performances. CER evaluates the reliability performance in the presence of multiple connections among devices and thus is not included in this study

Among these, three main metrics have been detected and defined. BER is commonly used to evaluate the decoding performance at the PHY layer, indicating the probability of an erroneous bit transmission. BLER is defined exclusively at the PHY layer and represents the ratio between the erroneous packets received and the totality of transmitted packets. Finally, PLR considers the erroneous transmission in the case of contiguous packets, evaluating the reliability at the MAC layer.

In [36], the authors compare the BER/BLER of different FEC candidates for high-throughput communications within factories, resulting from previous studies. While in [11], BER is used as a threshold for testing the WirelessHP PHY layer with different low-order modulations at different communications distances. A BLER threshold is defined in [114] to compare different FEC candidates' performance with the IEEE 802.11be PHY layer, assuming different industrial channel models. In [12, 13, 26], BLER and PLR are an upper bound for testing the IEEE 802.11 PHY layer performance assuming deterministic protocols.

In conclusion, the following metrics are recommended for the reliability analysis for Factory Automation. BLER provides a magnitude of the FEC capabilities and therefore is associated at the PHY layer. The reason is the following. The error rate for industrial communication refers to the packet, not the bits contained in it [120]. At the MAC layer, PLR defines the performance achieved by a particular retransmission scheme.

Furthermore, for a fair comparison between FEC candidates from different publications, it is crucial to incorporate additional factors into the analysis. Besides the different BLER results, other factors are the SNR, channel typology, and channel properties. Considering these elements, the analysis can provide a more comprehensive understanding of the candidates' performance and enable a more accurate comparison of their respective BLER results.

3.3.4 Latency: Decoding Latency

In industrial communications, latency is generally expressed as cycle time [4, 7, 26]. This metric expresses the latency between the data transmission and its reception. Three main processes affect this metric. The first one is the transmitter latency, which expresses the time elapsed between the data available at the MAC layer and its subsequent transmission by the PHY layer. Coding and modulation processes are parts of this period. Second, Propagation Latency represents the associated delay of the channel. Finally, the receiver latency considers the required time for demodulation and decoding. Moreover, for the criticality of the processes involved within the industrial environment, cycle time is commonly bounded by a maximum value T_{max}, which is half of the update rate period of the sensors and actuators included in the network [7].

An accurate estimation of the impact of the FEC on the latency performance of the wireless system is a complex measurement. Different and uncorrelated factors must be considered, such as the decoder architecture, the programming language, the interpretation of the algorithm's pseudo-code, and the hardware performance. In consequence, the comparison among different proposals is not straightforward.

The impact of Forward Error Correction FEC and related decoding algorithms on the latency for URLLC and Factory Automation applications has been the subject of various publications. Ferraz et al. [138] focus on Low-Density LDPC decoding latency and highlight its criticality for safety applications. Then latencies, in the order of 1 ms, are considered [7]. The authors consider this metric a trade-off between the system latency and throughput. Moreover, this work highlights that reduced decoding latencies are obtainable by optimizing the number of iterations of the decoding algorithm. Similarly, in their survey of decoding algorithms for various FEC schemes in URLLC, Shao et al. [115] emphasize the importance of reduced decoding latency for future ASIC developments. This parameter is crucial to meet URLLC use cases' latency requirements. Also, Zhan et al. [36], in their survey of FEC candidates for WirelessHP, consider decoding latency as one of the criteria for selecting an appropriate FEC scheme. Among the targets detected for WirelessHP, some, like Factory Automation and

Table 3.6: Impact of the decoding latency for Factory Automation use cases and similars in relevant journals

Author	Journal	Year	Applications considered in the study	Latency for the use cases [ms]
Ferraz et al.	IEEE Communications Surveys and Tutorials	2022	Decoding algorithms for LDPC for future scenarios. Safety is included	1 ms
Shao et al.	IEEE Communications Surveys and Tutorials	2019	ASIC decoders for 5G URLLC	-
Zhan et al.	IEEE Access	2018	WirelessHP	0.25 ms - 1ms
Fanari et al.	IEEE Open Journal of the Industrial Electronics Society	2022	FEC for Factory Automation wireless systems	0.25 ms - 1ms

Process Automation, assume use case latencies below or equal to 1 ms. Finally, Fanari et al. [9] detects the decoding latency as one of the main parameters for choosing FECs accurately for Factory Automation applications. Also, this work considers latencies close to 1 ms for Factory Automation applications.

Table 3.6 summarizes the key findings of this analysis. First, the articles considered belong to high-impact journals. Their content is relevant to this research topic. Furthermore, these have been published recently, between 2019 and 2022. This detail highlights the need for FEC schemes with reduced decoding latency, particularly for Factory Automation. Second, the application considered by the authors is also included. Indeed, this highlights the significance of FEC in the analyzed context. Finally, the latency values proposed by the authors for their use cases are also included.

$$Decoding\ Latency = \frac{Required\ Clock\ Cycles}{Decoder\ Clock\ Frequency} \tag{3.1}$$

As mentioned before, decoding latency is driven by several elements. Nevertheless, it is possible obtain an accurate estimation in an easy way. One of these is proposed in many works [18, 114, 140] and is represent by Equation 3.1. This metric helps assess the impact of FEC on system latency performance. Therefore, its accurate estimation is essential for selecting an appropriate FEC scheme for Factory Automation applications.

3.4 Summary

This chapter proposes two guidelines for defining use cases and metrics in the context of Factory Automation.

The first guideline suggests grouping use cases into three Fields of Application: Non-Critical, Critical, and Safety Communications, each with unique system performances related to Reliability, Latency, and Payload. Moreover, this first part compares the industrial wireless systems performance, introduced in Chapter 2, and the required performance of the Fields of Applications. This analysis highlights that there is no global coverage of the use cases requirements for Factory Automation.

The second guideline introduces two metrics for evaluating Forward Error Correction (FEC) techniques: Block Error Rate (BLER) and decoding latency. BLER measures the error ratio of the erroneous messages detected at the receiver while decoding latency represents the number of clock cycles for the decoding algorithm during the decoding step.

The chapter also highlights the need for further research on FEC applied in short packet transmissions. Indeed, traditional Shannon definitions are not efficient for this context.

Overall, these guidelines provide a framework for developing effective use cases and metrics for Factory Automation systems.

Chapter 4

Channel Coding for Industrial Wireless Communications

4.1 Introduction

The Chapter has two parts. In the first part, the metrics introduced in Chapter 3 are used for evaluating the candidates' performance in reliability and latency terms. BLER is associated with reliability, whereas decoding latency is for latency.

The reliability analysis is based on simulations conducted with the BCM toolkit, which simulates the data transmission between two nodes. Based on MATLAB, this simulator evaluates the BLER obtained for different SNR values. The candidates are compared with different payload lengths and code rates. In this study, only the AWGN channel is considered. In conclusion, for an established BLER threshold, the results are depicted in plots of Payload vs. SNR.

The latency, particularly the decoding latency, is evaluated as proposed in Equation 3.1, where this metric is defined as the required number of clocks per decoding. The number of clocks is associated with the decoding complexity of the algorithms. One or more decoding algorithms are chosen per each candidate from the following databases for each candidate: GoogleScholar, Scopus, and IEEEexplore.

Only one decoding algorithm is chosen per candidate. This choice is based on two key aspects. On the one hand, the capacity of the decoding algorithm to achieve high-reliability performance for short packet transmission. On the other hand, the presence of the parallel decoding property. Parallel decoding is necessary for the candidates to achieve low latency.

The second part of this Chapter proposes a Practical Application of the FECs in industrial scenarios. This analysis is conducted via a WLAN PHY layer simulator developed in MATLAB. The forthcoming IEEE 802.11be is considered.

The reason is twofold. First, this standard will be the first of its family developed for industrial communications. Second, the study proposes some candidates for future standard development. The different FECs included in this simulator are evaluated with industrial channel models, CM8 and Scenario7, respectively, taken from [141] [14].

Only reliability is considered in this analysis and represented in plots of SNR vs. BLER.

The Summary Section contains the conclusions

4.2 Candidates

This section proposes FEC candidates for FA scenarios. The choice is based on the techniques proposed in Table 2.3, 2.4 and 2.5. Among all the analyzed techniques, the choice falls on QC-LDPC, Polar, PCCC, and TBCC, due to their high reliability in short packet regime and the opportunity to implement parallel decoding.

Table 4.1: Encoding Methodologies

Candidate	Method	General Advantages	General Disadvantages	Ref
QC-LDPC	PEG	High reliability for reduced payload size	Reduced reliability from payload sizes>200 bit	[142]
QC-LDPC	Photograph	High reliability for every payload size	CRC concatenation is required in Short Packet Regime	[51]
Polar	Arikan's Polar	High Decoding Performance for large packets	Poor decoding performance for short packet transmissions	[143]
Polar	CA-POLAR	High decoding Performance for short packet transmissions	More latency than Arikan's Polar	[70–72]
Polar	PAC POLAR	High decoding Performance for short packet transmissions	Actually no hardware implementations are published	[144]
PCCC	Narayan's Model	Reduced Complexity	Poor decoding performance, High latency	[145]
PCCC	Souza's Model	Reduced Complexity	Poor decoding performance	[146]
PCCC	LTE Encoder	High decoding performance	High complexity	[147]
CC	TBCC	High Decoding Performance	High Complexity	[100]
CC	ZTBCC	High decoding performance, Reduced Complexity	Reduced Code Rate	[100]

4.2.1 QC-LDPC

QC-LDPC is a subfamily of LDPC. The linear relationships between the information block with K bits and the one encoded with N bits are defined using a Parity Check Matrix (H). H has dimension $N \times N - K$, and it is composed only by elements with one or zero as values. Its principal property is sparsity, which means that most of the matrix element values corresponding to zero, allowing, as a consequence, its representation using the Tanner Graph. This graph comprises N nodes, the variable nodes, and further $N - K$ nodes, the check nodes. Comparing QC-LDPC with the other subfamilies, its H presents the Quasi Cyclic property, enabling full parallel decoding. Indeed, such property derives from the high sparsity of the matrix, allowing to divide H into several sub-matrices. The literature offers two methods for generating H in the case of QC-LDPC. By probabilistic approach such as the Photograph method [51], or based on the Power Edge Growth (PEG) method [142] which is an iterative algorithm used for the graph generation.

The Photograph method consists of repetition techniques applied to a base matrix [148]. The main benefits are high reliability for variable lengths of both K and Code Rate, as demonstrated by the version implemented in 5G NR [149]. Nevertheless, when used for short packet transmissions, there may be error floors at higher SNR levels, which is a disadvantage.This problem can be solved by concatenation with CRC [53, 54]. Among the obtained FEC by Photograph method, there are the *accumulate-repeat-3-accumulate* (AR3A) and *accumulate-repeat-by4-jagged-accumulate* (AR4JA) proposed by the Jet Propulsion Laboratory [150, 151].

The second proposal, the PEG method, is an iterative form for generating H, which aims to establish connections between the Tanner Graph nodes. These iterations produce girth maximization, which allows high-decoding performance in short packet communications. The term girth defines the largest cycle in the Tanner Graph. For more details about the algorithm, see [75]. However, their performance tends to deteriorate as the size of the information increases. The QC-PEG-LDPC have been considered as potential candidates in 5G NR for URLLC [127] assuming K of 40 bits and 200 bits. The results recognize benefits by using this method in the 40 bit case. In [149], the authors recommend the use of the PEG within the QC-LDPC structure adopted in 5G NR for ensuring better performance in the short packet regime. Table 4.1 summarizes the main features of the proposed methodologies. Among them, in this Chapter is recommended the use of the photograph within FA wireless systems. Indeed, high-reliability performance occurs for a wider variety of data sizes, and code rates respect the PEG method.

4.2.2 Polar

Polar codes were designed in the late 2000s by Arikan [143], providing for the first time a FEC technique able to achieve the channel capacity. The main feature of Polar is the use of binary-input discrete memoryless channels (B-DMC) W, where a method known as channel polarization is applied. Channel polarization splits W into a perfect channel and a noisy channel, allowing the transmission of the K information through the perfect channels. At the same time, the redundant $N - K$ bits pass along the noisy channels. The noisy channel bits are known as Frozen bits. Such sequence is also known to the receiver. Then, a generator matrix G encodes the generated data vector.

Early Polar results did not provide the expected performance [152], in particular in the Short Packet regime [70]. This problem was solved by the use of concatenation techniques. There are currently two proposals, one consists of concatenation with CRC, known as CRC-Aided Polar (CA-POLAR) [70–72], while the other proposes CC and is known as PAC [144]. Recently, in [153, 154] an optimal Polar code design for industrial environments is presented.

The high performance achievable by CA-POLAR codes makes them a viable option for designing wireless systems for FA communications. As shown in Table 4.1, these techniques offer high reliability in the short packet regime, and there are hardware implementations with promising results.

4.2.3 PCCC

PCCC codes are a subfamily of Turbo codes [101]. The encoder is designed to connect two convolutional encoders, which produces the parity bits. In addition, a puncturing block ensures the encoding for several code rates. The PCCC encoder includes one or more interleaving blocks to improve the decoding performance. In a survey on Turbo Coding for HARQ, Chen et al. [155] identify three main Turbo Encoders: Narayanan model [145], Souza model [146] and LTE Turbo encoder [147], which differ in the number and placement of interleavers.

The Narayan model foresees the use of two interleavers: one placed before the encoders and the other before the second encoder. The Souza model involves using a single interleaver set before the second encoder. However, these models do not show successful decoding during the first frames transmission [155]. In the LTE Turbo model, four interleavers solve this issue, the first one placed between the two parallel encoders and the others in correspondence with the systematic bit sequence and the obtained parity bits. Moreover, LTE Turbo presents a circular buffer that solves the decoding problems encountered in the other models.

Table 4.1 summarizes the main features of the encoder models for PCCC. Among the analyzed codes, LTE turbo performs better decoding than its counterparts, making it a favorable candidate among the proposed models.

4.2.4 Padded CC

CC with padding reduces the typical high decoding probability that occurs during the first data stream transmitted [100]. Two main padding strategies permit the distinction of this subfamily into TBCC and ZT-BCC. TBCC requires that encoder and decoder structures have the same initial and final states. Consequently, the padding sequence is included in the encoded block, showing benefits in the decoding performance, particularly for short packet transmissions, moreover avoiding the code rate loss, as defined in Equation 4.1.

$$R = \frac{K}{N + padding\ bit} \tag{4.1}$$

In ZTBCC, the padding is an additional element of the encoded stream. The decoded block is composed of stream and padding bits in this case. This structure affects the code rate as described in Equation 4.2.

$$R = \frac{K}{N} \tag{4.2}$$

Table 4.1 summarizes the main features of the models of CC with padding. Among these models, the authors recommend using the TBCC codes for their high decoding performance in the short packet regime and the absence of code rate loss.

4.3 Decoding Algorithms

As highlighted in previous sections, the integration of FEC techniques can be a crucial element for guaranteeing the performance of wireless systems in FA use cases. One reason is associated with the properties of the propagation channels in industrial environments. The high time coherence of industrial propagation channels makes the use of some MAC layer techniques useless, such as time re-transmission techniques [12].

The usage of robust FEC techniques could improve the MAC-layer performance [153, 154]. The FECs are techniques that detect and correct the erroneous bit included in the received data. Many propagation effects correlated to the channel models cause these errors during the data transmission, such as noise, interference, and fading. Among these, fading is particularly critical within industrial environments. More specifically, the encoder located in the transmitter converts a block of K information bits into a longer block of N bits, which contains N-K redundant bits. Such redundancy helps the decoding architecture, located in the receiver, detect and correct the erroneous bits. After these corrections, the original K information is ultimately reconstructed.

The literature offers numerous decoding architecture proposals to obtain specific reliability, latency, or energy consumption goals. For example, faster decoding is typically allowed by a low complex structure despite the expense of reliability. Commonly, many industrial scenarios, such as Process Automation, adopt low-complex decoding architectures. In these cases, high density node networks are required to control and monitor the processes, where the nodes must communicate fast and at the same time, maintain a reduced energy consumption. On the contrary, the FA processes demand complex decoding architectures to meet the strict requirements of the use cases. High reliability and low latencies are achievable with decoding architectures that include a high level of parallelism and sophisticated decoding algorithms [36]. To further improve the reliability, typically, the demodulated N bits are estimated by using the Logarithmic Likelihood Ratio (LLR) method [156].

Tables 4.2, 4.3 and 4.4 show a comparison of the decoding algorithms developed for short packet transmissions over the years. The comparison considers both the algorithmic complexity and the reliability.

In this Chapter, the definition of Algorithmic complexity refers to the number of required clock cycles during the decoding. The presence of parallel decoding reduces the number of cycles needed. In the analyzed literature, parallel decoding can be semi-parallel or fully parallel. Among the reviewed works, in [157] the case of full parallel decoding is defined as available. Moreover, if the algorithms are iterative, another parameter is the number of iterations.

The clock cycle complexity allows the estimation of decoding latency in short packet transmissions, and thus in FA, as highlighted in [115,128,158]. In this work, the complexity is related to the parameters N, P, L, R, K and finally m. N defines the block length, R is the code rate, whereas $K = NR$. P defines the number of updated nodes in the decoder. Considering full parallel decoding, $N = P$. The parameters L and m define the number of lists used in the SCL algorithm and the memory length in WAVA. Finally, the reliability analysis consists of both BLER and BER. BLER values differ from BER ones for the presence of the symbol*. The presence of blanks defines the absence of information in the literature regarding the specific parameters. Most decoding algorithms are evaluated with the AWGN channel, whereas in [159] is included a Rayleigh channel.

4.3.1 LDPC

In LDPC codes, the literature suggests using iterative decoding algorithms. Such algorithms allow the message passing between variable nodes and check nodes. The message passing can also be defined as message exchange. Min-Sum and Belief Propagation (BP) are the algorithms adopted in QC-LDPC. Both algorithms have a complexity tending to $\frac{N}{P}$ per iteration due to the full parallel decoding.

Broulim et al [160] and Balatsouka-Stimming et al [161] offer an implementation of MIN-SUM with full parallel decoding. In the case of BP, full parallel decoding is proposed in the works of Li et al [162], Yesil et al [163] and Yen et al [164]. Other MIN-SUM implementations in which semi-parallel decoding is proposed are [165–167], while for BP case there is the proposal of [168]. In terms of reliability, BER of 10^{-6} at SNR values close to 4 dB are achieved in [161, 167] via FPGA implementation. Nevertheless, [162] offers a BER of 10^{-9} at equal SNR. BP-based algorithms offer higher reliability than MIN-SUM-based algorithms due to the higher number of required operations [169]. However, the number of operations does not affect the number of clocks required per iteration, as shown in Table 4.2.

In conclusion, BP and, in particular, the model [162] are optimal, from the complexity point of view, offers full parallel decoding. In contrast, in terms of reliability, [162] is the best performing model among the proposals analyzed.

4.3.2 Polar

Polar implementations for short packet communications scenarios use algorithms based on the concept of erasure, i.e., the message decoding consists of erasing the interference affecting the received K LLRs and the iterative reconstruction of the message. Cancellation-based algorithms include Successive Cancellation (SC), Successive Cancellation List (SCL), and Successive Cancellation Flip (SCP), while the iterative algorithms proposed by the lettering are BP, OSD, and Sphere.

The proposals with SC show semi-parallel decoding, moreover, the clock complexity varies from a value tending to $2log_2(\frac{N}{P})$, as in the case of Kam [170] and Ercan's 2017 [171] models, up to a maximum tending to $\frac{N}{P}$, as in the case of Leroux's model [172], Yuan's 2014 [173] and Giard's [174]. Regarding reliability, the 2017 Ercan model is the best result up to date, offering a BLER of 10^{-5} at SNR of 4 dB (FPGA implementation). Even in the case of SCL have been proposed semi-parallel decoding architectures. These models show complexities ranging from $\frac{N}{2} + \frac{N}{P}log_2\frac{N}{4P}$ clock cycles, as in the case of Yuan's 2015 model [175], up to a complexity tending to $2N + \frac{N}{P}log_2N$. In this last case have been included the models of Balatsoukas-Stimming [176], Xiong [177], Lin [178] and Fan [179] Concerning reliability, Balatsoukas-Stimming and Lin offer the best performance for a Block Length of 1024 bits. Both of them are implemented on ASIC and provide BLER of 10^{-6} for SNR close to 4 dB. Erkan in 2020 offers an alternative to SCL by introducing the SCF algorithm, which provides similar reliability to Lin and Fan models, with a reduced complexity $\frac{N}{3P}$ [180]. The Ercan model is currently the first implementation of SCF. In the specific, an ASIC has been used for the model [180]. Also, the implementation of the Sphere algorithm [157, 181, 182] reveals promising for reduced block lengths. However, the information on the hardware implementation of this approach is scarce. Similarly addressed is the use of the OSD algorithm [139].

Among the various proposals examined, the BP algorithm [183] appears to be the least efficient for Polar codes. In conclusion, SCL-based implementations are the most efficient in complexity and reliability. Nevertheless, SCF is just a promise, and further investigation regarding this novelty is necessary.

4.3.3 PCCC

PCCC code implementations support the use of Log-MAP-based algorithms that enable iterative decoding. Generally, all of the models allow semi-parallel decoding, with complexities tending to $\frac{2N}{P}$. Such models are Bougard's [184], Wong's [185] and Xiang's [186]. Further implementations are Shin's model, with complexity tending to $\frac{N}{P}$ [187], and Maunder's model [159] resulting so far the only proposed full parallel decoding for PCCC. Both models implement MAP. Among the different models, Wong's model performs better in terms of reliability due to an ASIC implementation ensuring a BLER of 10^{-5} at SNR of 1.75 dB, 2.25 dB, 3 dB, for 512 bit, 256 bit, and 128 bit block sizes, respectively.

4.3.4 TBCC

In the TBCC case, iterative algorithms such as WAVA [188] [189], CVA [190], and OSD [191] are proposed for short packet transmissions. However, performance results are only available for WAVA-based proposals. In particular, the ZTE model suggested for the 5G NR standard provides a semi-parallel architecture with a complexity per iteration tending to $\frac{N}{P}$ [188].

Table 4.2: Hardware Implementation Part I

Author	**FEC**	**Decoding Algorithm**	**Block Length [Bit]**	**Code Rate**	**Hardware Implementation**	**Parallel Decoding**	**Number of Iterations (MAX)**	**Required Clock Cycles**	**BER/ BLER***	**SNR [dB]**	**Ref**
Park et al	LDPC	MIN-SUM	672	0.5	ASIC	Semi-Parallel	10	$\frac{5N}{P}$	10^{-7}	4	[165]
Xiang et al	LDPC	MIN-SUM	2304	0.5	ASIC	Semi-Parallel	10	$\frac{N}{P}$	10^{-6}	3	[166]
Broulim et al	LDPC	MIN-SUM	64	0.5	FPGA	Full			10^{-7}	6.75	[160]
Broulim et al	LDPC	MIN-SUM	128	0.5	FPGA	Full			10^{-7}	6	[160]
Broulim et al	LDPC	MIN-SUM	256	0.5	FPGA	Full			10^{-7}	4.75	[160]
Chandrasetty et al	LDPC	MIN-SUM	576	0.5	FPGA	Semi-Parallel	10	$\frac{N}{P}$	10^{-6}	4.25	[167]
Chandrasetty et al	LDPC	MIN-SUM	1152	0.5	FPGA	Semi-Parallel	10	$\frac{N}{P}$	10^{-6}	3.75	[167]
Chandrasetty et al	LDPC	MIN-SUM	2304	0.5	FPGA	Semi-Parallel	10	$\frac{N}{P}$	10^{-6}	3.5	[167]
Balatsoukas-Stimming et al	LDPC	MIN-SUM	1000	0.5	FPGA	Full	10	$\frac{2N}{P}$	10^{-6}	3.5	[161]
Balatsoukas-Stimming et al	LDPC	MIN-SUM	1152	0.5	FPGA	Full	10	$\frac{2N}{P}$	10^{-6}	3.5	[161]
Balatsoukas-Stimming et al	LDPC	MIN-SUM	1152	0.5	FPGA	Full	10	$\frac{2N}{P}$	10^{-6}	4.25	[161]
Petrovic et al	LDPC	Layered BP	2304	22/68	FPGA	Semi-Parallel	10	$\sim\frac{N}{P}$	$10^{-4}*$	-0,75	[168]
Yesil et al	LDPC	Layered BP	2304	0.5	FPGA	Full	10	$\frac{N}{P}$	10^{-8}	3.25	[163]
Petrovic et al	LDPC	Flooding BP	2304	22/68	FPGA	Semi-Parallel	10	$\sim\frac{N}{P}$	$10^{-5}*$	0.25	[168]
Yen et al	LDPC	BP Based	672	0.5	ASIC	Full	11	$\frac{N}{P}$	10^{-7}	6	[164]
Li et al	LDPC	BP	576	0.5	FPGA	Full	10	$\frac{NR}{P}$	10^{-9}	4.5	[162]
Wu et al	POLAR	OSD	128	0.5					$10^{-4}*$	4	[139]
Wu et al	POLAR	OSD	256	0.5					$10^{-3}*$	4	[139]
Kam et al	POLAR	SC	1024	0.5	ASIC	Semi-Parallel		$2log(\frac{N}{4P})$	10^{-4}/ $10^{-5}*$	3.5	[170]
Leroux et al	POLAR	SC	1024	0.5	FPGA	Semi-Parallel		$\frac{N}{P}log2(\frac{N}{4P})$	10^{-5}/ $10^{-4}*$	3.75	[172]
Yuan et al	POLAR	SC	1024	0.5	FPGA	Semi-Parallel		$1,5N-2$			[173]

Table 4.3: Hardware Implementation Part II

Author	FEC	Decoding Algorithm	Block Length [Bit]	Code Rate	Hardware Implementation	Parallel Decoding	Number of Iterations (MAX)	Required Clock Cycles	BER/ BLER*	SNR [dB]	Ref
Ercan et al	POLAR	SC	1024	0.5	FPGA	Semi-Parallel		$\frac{log_2 N+1}{P}$	10^{-7} $10^{-5}*$	4	[171]
Ercan et al 2020	POLAR	SC	1024	0.5	ASIC	Semi-Parallel		$\frac{N}{3P}$	$10^{-6}*$	3.5	[180]
Tajima et al	POLAR	BP	128	0.5			8	$\sim 2N + 2NR$	$10^{-4}*$	6	[183]
Husmann et al	POLAR	Sphere	128	0.5		Avaiable		$\frac{2^K}{P}$	10^{-6}	4	[157]
Piao et al	POLAR	Sphere	64	0.5				$LNlogN$	$10^{-5}*$	2	[181]
Hashemi et al	POLAR	List Sphere	1024	0.5	ASIC	Semi-Parallel		$Nlog_2 N - 1$	10^{-5}/ $10^{-4}*$	3	[182]
Yuan et al	POLAR	SCL	1024	0.5	ASIC			$\sim \frac{N}{2} + (\frac{N}{P})log2(\frac{N}{4P})$	$10^{-4}*$	2.5	[175]
Yuan et al	POLAR	SCL	1024	0.5	ASIC			$\sim N + (\frac{N}{P})log2(\frac{N}{4P})$	$10^{-4}*$	2.5	[175]
Balatsoukas-Stimming et al	POLAR	SCL	1024	0.5	ASIC	Semi-Parallel		$(2 + R)N + (\frac{N}{P})log(\frac{N}{4P})$	$10^{-6}*$	4	[176]
Xiong et al	POLAR	SCL	1024	0.5	ASIC			$3\frac{N}{NR} + \frac{NL}{P}log\frac{NL}{8P}$	10^{-4}/$10^{-2}*$	2.6	[177]
Lin et al	POLAR	SCL	1024	0.5	ASIC	Semi-Parallel		$\sim 2N + \frac{N}{P}log_2\frac{N}{4P} + \frac{R}{N}$	$10^{-6}*$	3.6	[178]
Fan et al	POLAR	SCL	1024	0.5	ASIC	Semi-Parallel		$3N + \frac{N}{P}log_2\frac{N}{4P}$	$10^{-5}*$	2.5	[179]
ZTE	TBCC	WAVA	100			Semi-Parallel	2	$\frac{N}{P} + 60$			[188]
Wang et al	TBCC	CVA	40				20		$10^{-6}*$	5	[190]
Zhou et al	TBCC	ML+OSD	144	0.5					$10^{-6}*$	1.75	[191]

Table 4.4: Hardware Implementation Part III

Author	FEC	Decoding Algorithm	Block Length [Bit]	Code Rate	Hardware Implementation	Parallel Decoding	Number of Iterations (MAX)	Required Clock Cycles	BER/ BLER*	SNR [dB]	Ref
Liang et al	TBCC	WAVA	128	0.5			10	$\sim N2^m$	10^{-6}*	3.5	[189]
Shin et al	Turbo	Log Map	1024	0.3	ASIC	Semi-Parallel	6	$\sim \frac{N}{P}$	10^{-5}	0.8	[187]
Bougard et al	Turbo	SW Map	128	0.3	FPGA		6		10^{-7}	6	[184]
Bougard et al	Turbo	SW Map	64	0.3	FPGA	Semi-Parallel	6		10^{-8}	5.5	[184]
Wong et al	Turbo	SW MAP	512	0.3	ASIC	Semi-Parallel	8	$\sim \frac{2N}{P}$	10^{-5}	1.75	[185]
Wong et al	Turbo	SW MAP	256	0.3	ASIC	Semi-Parallel	8	$\sim \frac{2N}{P}$	10^{-5}	2.25	[185]
Wong et al	Turbo	SW MAP	128	0.3	ASIC	Semi-Parallel	8	$\sim \frac{2N}{P}$	10^{-5}	3	[185]
Xiang et al	Turbo	APTD	64	0.3		Semi-Parallel	8	$\sim \frac{2N}{P}$	10^{-5}*	5.25	[186]
Xiang et al	Turbo	APTD	512	0.3		Semi-Parallel	8	$\sim \frac{2N}{P}$	10^{-5}*	2.5	[186]
Xiang et al	Turbo	ML-MAP	64	0.3		Semi-Parallel	8	$\sim \frac{2N}{P}$	10^{-5}*	7.25	[186]
Xiang et al	Turbo	ML-MAP	512	0.3		Semi-Parallel	8	$\sim \frac{2N}{P}$	10^{-5}*	2	[186]
Maunder et al	Turbo	Log MAP	480	0.3		Full	8	$\sim \frac{2N}{P}$	10^{-5}*	3	[159]
Maunder et al	Turbo	Log MAP	48	0.3		Full	8	$\sim \frac{2N}{P}$	10^{-5}*	7	[159]

4.4 Short-Packet Coding Performance Results

This section compares the candidate codes presented in Section III, i.e., QC-LDPC, Polar, TBCC, and PCCC. The analysis is based on a comparison of their reliability and latency performances. Reliability is analyzed using MATLAB simulations based on BLER metrics. Finally, latency is evaluated as decoding latency, following the approach proposed by previous works [18, 114, 140]. The decoding algorithms were previously suggested in Section IV.

4.4.1 Preliminaries

The suggested metrics are applicable to comparisons among different FEC techniques, offering reliability and latency performances for various payload sizes. The BLER represents the reliability metric. For the latency evaluation, the decoding latency is optimal for focusing on the PHY layer performance. Finally, the proposed payload lengths are 16 B, 32 B, and 64 B. Concerning the decoding latency evaluation, its calculation is available by counting the number of clocks required in the decoding complexity. For this analysis, the results offered in Section 4.3 are the reference. The FEC candidates compared in this section are QC-LDPC, CA-POLAR, LTE TURBO, and TBCC. QC-LDPC and CA-POLAR are in the 5G NR standard, while TURBO and TBCC are part of LTE. Furthermore, QC-LDPC has coupled to the Belief Propagation algorithm, CA-Polar to an SCL with $L = 2$ and a CRC of 24 bits, while LTE Turbo uses Log-MAP finally, TBCC with WAVA.

4.4.2 Reliability

The reliability analysis discussed in this Section aims to evaluate the performance of the candidates expressed in terms of BLER at different payload lengths. The BLER threshold value is taken by the reliability comparisons proposed in [36], which surveyed and analyzed different FEC techniques candidates for WirelessHP.

4.4.2.1 Simulation Platform

BLER values have been obtained with a specifically developed MATLAB workbench depicted in Figure 4.1, which provides simulation results to compare different FEC techniques with code rates 1/3 and 1/2. The code rate at 1/2 is a well-known configuration for industrial communications [36], whereas the case of 1/3 is a configuration proposed for 5G NR for the signaling transmission of the Physical Broadcast

Channel [192], also targetted for short packet communications. In this case, the data size varies between 40 and 100 bits. The blocks comprised in the simulator are the following.

- Encoder, which includes the different candidates
- QPSK modulator included in the communications toolbox.
- AWGN channel taken from the communication toolbox.
- QPSK demodulator, as the modulator is part of the communications toolbox.
- Decoder that selects the decoding algorithm previously selected for each candidate.

The simulations assume QPSK modulation over an AWGN channel. Further simulation parameters are the number of transmissions per simulation point ($3 \cdot 10^6$ to obtain a BLER threshold of 10^{-6}). The SNR curve is obtained with a step of 0.25 dB. The parameters are summarized in Table 4.5.

Table 4.5: Simulation Parameters for FEC candidates comparisons

Parameter	**Values**
Payload [B]	16, 32, 64
Nº transmitted data	$3 \cdot 10^6$
Modulation	QPSK
dB steps	0.25
Channel	AWGN
Code Rate	1/2,1/3
BLER threshold	10^{-6}

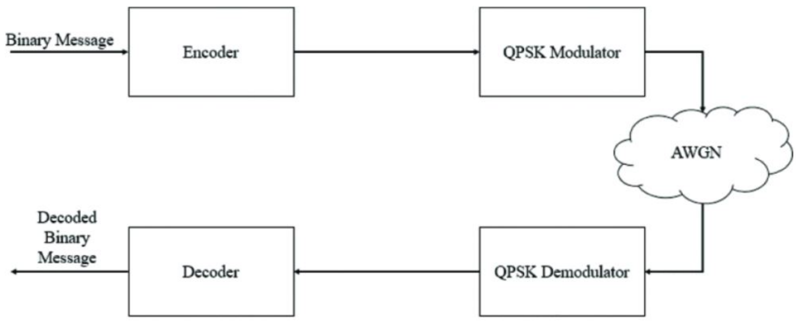


Figure 4.1: Block Diagram of the Matlab Simulation Platform

4.4.2.2 Results

Figure 4.2 and Figure 4.3 display the simulation results. The curves show the variation of reliability as a function of the payload size. The vertical axis represents the payload values, while the horizontal axis shows the SNR values obtained for each BLER threshold.

Figure 4.2 presents the threshold values for code rate 1/3. The figure shows how the SNR for different payload sizes varies according to the FEC employed. It is possible to observe how for the range 16-32 B QC-LDPC and CA-POLAR provide similar performance while CA-POLAR is better for 16 B payloads. CA-POLAR lacks the threshold for

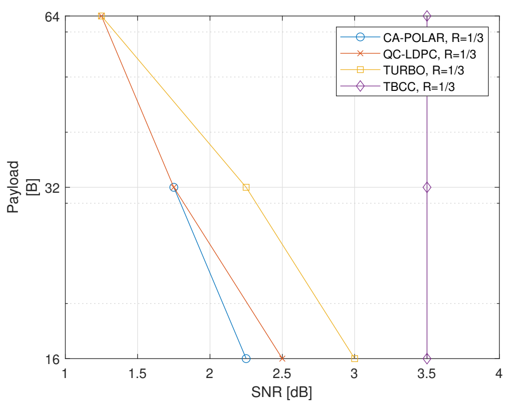


Figure 4.2: Reliability Results for R =1/3

64 B due to its specific design in the 5G NR standard. In the 64 B case, QC-LDPC and LTE TURBO have comparable performance. Finally, analyzing TBCC, a constant threshold can be observed as a function of the different payload lengths because it is a CC type.

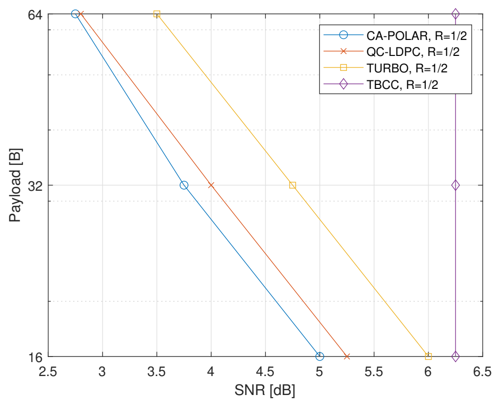


Figure 4.3: Reliability Results for R =1/2

Figure 4.3 shows the threshold values for code rate 1/2. First, is is observed that CA-POLAR provides the best performance in all considered ranges. However, QC-LDPC gets closer when the payload is 64 B. LTE TURBO offers 16 dB lower performance than CA-POLAR, whereas TBCC only offers comparable performance to LTE TURBO for 16 B.

The results suggest the following significant conclusions. First, CA-Polar and QC-LDPC outperform the other candidates. Nevertheless, CA-Polar shows slightly better performances. Among the candidates, TBCC offers the worst decoding performance. Second, the variation of payload sizes affects the decoding performances of the candidates, except for TBCC. Indeed, reducing the payload value increases the SNR required to reach the BLER threshold.

4.4.3 Latency

Decoding latency is defined using Equation 3.1. However, this definition requires a previous step, which regards the estimation of the algorithmic complexity in terms of cycle clocks. Table 4.6 shows required clock cycles associated with the decoding algorithm choices (It and P correspond to the number of iterations and parallel processes, respectively). BP and Log-MAP enable full parallel decoding, while SCL and WAVA only allow semi-parallel decoding. For CA-POLAR, $P = 32$ was assumed for payloads of 16 B, since [179] does not consider such low payload sizes. Table 4.7 shows both the count of clocks required by the decoding algorithm and the corresponding decoding latencies. The number of clock cycles respects the values of the parameters shown in Table 4.6. The decoding latency calculation is performed as defined in [140].The clock frequency is considered at 300 MHz. This choice is motivated by the similar clock frequencies performed by the FPGA models used in [11, 17]. In [11] a Spartan DS610 is used, whereas [17] proposes a Xilinx 7035i Zynq SoC.

The results show that QC-LDPC and LTE TURBO provide very low decoding latency due to the full parallel decoding, ensuring constant values as the block length varies. QC-LDPC provides a decoding latency of $0.017\ \mu s$ and $0.01\ \mu s$ respectively for code rates of 1/2 and 1/3, while LTE TURBO provides a constant decoding latency of $0.053\ \mu s$. Although CA-POLAR does not offer a fully parallel architecture, it allows low latency decoding for 16B and 32B. In the case of 16 B, it guarantees $0.027\ \mu s$ for code rate 1/2 and $0.13\ \mu s$ for code rate 1/3, while for 32 B, it offers $0.05\ \mu s$ and $0.13\ \mu s$ respectively. Finally, in the case of 64B the decoding latency obtained is $0.11\ \mu s$. In conclusion, the best performing choice in terms of latency is the QC-LDPC.

Table 4.6: Proposed Decoding Algorithm

FEC	**Decoding Algorithm**	**Author**	**Decoding Architecture**	**Required Clock Cycles**	**Iterations**	**P**	**Ref**
QC-LDPC	BP	Li et al	Full Parallel	$\frac{NR}{P}$	10	N	[162]
CA-POLAR	SCL	Fan et al	Semi Parallel	$\frac{N}{P} log_2 \frac{N}{4P}$		64	[179]
LTE TURBO	Log-MAP	Maunder et al	Full Parallel	$\frac{2N}{P}$	8	N	[159]
TBCC	WAVA	ZTE	Semi Parallel	$\frac{N}{P} + 60$	2	128	[188]

Table 4.7: Decoding Latency results for a Decoding Clock Frequency of 300 MHz

FEC	Clock Cycles						Decoding Latency [μs]					
	16B		32B		64B		16B		32B		64B	
	R=1/2	R=1/3	R=1/2	R=1/3	R=1/2	R=1/3	R=1/2	R=1/3	R=1/2	R=1/3	R=1/2	R=1/3
QC-LDPC	5	3	5	3	5	3	0.017	0.01	0.017	0.01	0.017	0.01
CA-POLAR	8	20	16	20	32		0.027	0.067	0.05	0.13	0.11	
LTE TURBO	16	16	16	16	16	16	0.053	0.053	0.053	0.053	0.053	0.053
TBCC	124	126	128	132	136	144	0.41	0.42	0.43	0.44	0.45	0.48

4.5 Practical Application: Comparative analysis of FECs for future evolution of IEEE 802.11be

This Section introduces the second part of the study developed for this Chapter. This part provides a background of the scenario and the developed simulator.

The scenario is characterized by established dimensions and by two industrial channel models. The channel models are the CM8, adopted in the IEEE 802.15.4a standard, and Scenario 7, which is a result taken from [14].

The description of the simulator starts with the definition of the IEEE 802.11be PPDU. Indeed, the simulator represents this architecture. Then, the architecture is described. At this step, the simulator provides the following FECs: WLAN LDPC and CC, 5G NR LDPC, and 4G LTE Turbo. This Section finishes with the establishment of the simulation parameters.

4.5.1 Discussion on Factory Automation Scenarios

This section reviews the main challenges of wireless communications for FA, examining the main characteristics of some of the channel models proposed in the literature. After discussing the main features of the channels, there is an analysis of the main problems inherent in designing wireless systems within industrial environments.

4.5.1.1 Proposed Industrial Channel Models

This Chapter studies the performance of the FECs within IEEE 802.11be, taking into account three different channel models (CM). One of them is the AWGN channel. The other two models are Scenario 7 and CM8 and represent industrial environments. These models are based on the developments by Molisch et al. [141] and on the experimental results shown in Reference [14].

Both describe NLOS scenarios. These channels are both based on the Saleh-Valenzuela model. Furthermore, they represent environments for communications having lengths between 2 m and 8 m. Both models present a path loss model composed of free space path losses and shadowing components. The shadowing component is characterized by a log-normal distribution with zero mean and $\delta = 6$ dB [193]. Both channels exhibit a coherence time of 30 ms. The coherence time of the channel is longer than the required E2E minimal latencies of the use cases addressed in this Chapter. Thus, re-transmission techniques, such as TDMA for reliability improvement, are not beneficial, as discussed in Reference [12, 13].

4.5.1.2 Discussion on Factory Automation Wireless System Design

As seen in Section 4.5.1.1, the Scenario 7 and CM8 channels have a coherence time higher than the FA control cycle requirements; thus, the time-based re-transmission techniques do not provide the desired reliability effects [13]. Therefore, the first step to increase wireless systems' reliability is to include more robust FECs.

Now, the discussion passes to the control cycle time challenge. The Control cycle time defines when the master sends data to all sensors connected to the network. Considering that Scenario 7 and CM8 describe environments close to 10 m $\times$ 10 m, it is possible to assume a network inside these areas, composed approximately of 20 slaves connected to an Access Point in the middle of the room, which is a commonly used configuration in these environments [12]. Therefore, considering a control cycle time of 10 ms, each slave must transmit 20 PPDU in a maximum time of 0.5 ms.

Hence, to guarantee low latency values, it is necessary to send short data. As analyzed in several publications [132, 194], there are specific FECs for transmitting short-sized data. The aim of these techniques is the simultaneous fulfillment of reliability and latency requirements. The latter condition is usually satisfied by the use of parallel decoding architectures.

4.5.2 IEEE 802.11be PPDU Format

IEEE 802.11be will offer a new design of the physical layer convergence protocol data unit (PPDU) (Figure 4.4). The PPDU structure is splittable into four main blocks: Legacy Preamble, Extremely High Throughput (EHT) Preamble, and data.

This new standard will include backward compatibility, and, indeed, for this reason, the PPDU will contain the same legacy preamble structure introduced in IEEE 802.11a [16, 195]. On the other hand, it will introduce the concept of forwarding compatibility in the IEEE 802.11 family. The long universal SIG (U-SIG) and the EHT-SIG will provide forwarding compatibility. U-SIG is composed of two OFDM symbols, defined as Version Dependent Information and Version Independent Information. The Version Dependent Information will provide mechanisms similar to the HE signal field used in IEEE 802.11ax [195]. The following EHT-SIG field preamble will reserve future IEEE 802.11be features not included in the U-SIG, and it will be composed of common field and user-specific field, here information relevant for future communications, such as new FECs, will be added [195]. Finally, the short training field (EHT-STF) and long training field (EHT-LTF) preambles follow the same function as those offered in IEEE 802.11ax, i.e., fine-time and frequency tuning when using techniques, such as MIMO and OFDMA [195].

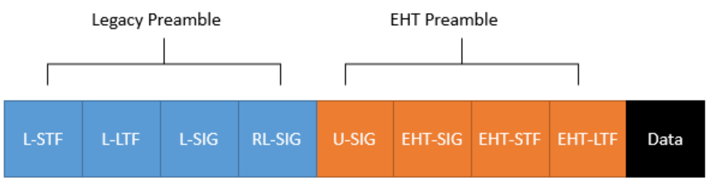


Figure 4.4: IEEE 802.11be PPDU format.

4.5.3 Platform Architecture

The platform is based on the WLAN toolbox of MATLAB, and it offers the transmission of the IEEE802.11be waveform among two nodes. In Figure 4.5, the simulation steps are represented with a block diagram model. After the PSDU generation, there is its passage to the

WLAN Waveform Generation block, where the PPDU is generated. The PSDU configuration requires the following parameters: PSDU length, Modulation Coding Scheme (MCS), guard interval, channel coding, and channel bandwidth.

Then, the obtained waveform, represented by tx in Figure 4.5, passes through the channel. In the simulator, three different channels are available: Scenario 7, CM8, and AWGN.

On the receiver, the first steps consist of the OFDM demodulation of the received signal rxn and its equalization. Moreover, regarding Scenario 7 and CM8 scenarios, the ideal channel estimation is applied before the OFDM demodulation. Then, the obtained symbols pass to the Bit Recovering block, which consists of two main phases: demapping and decoding.

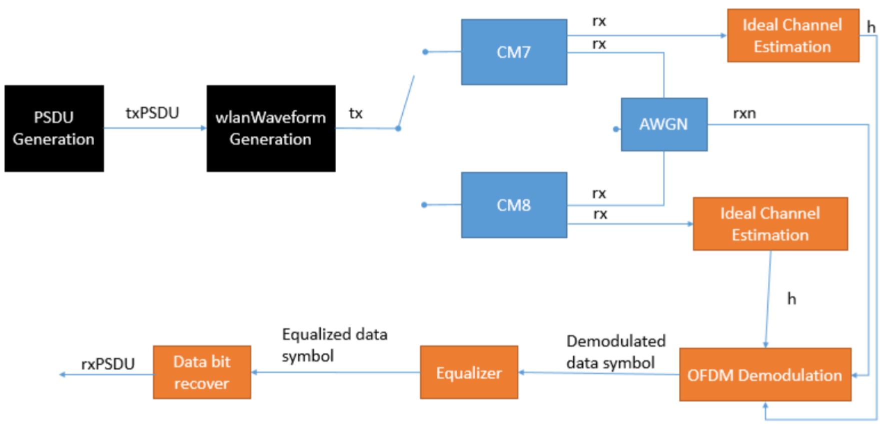


Figure 4.5: Block diagram model for reliability analysis.

4.5.3.1 Data Transmission Block

The wlanWaveform generation block (Figure 4.6) generates the entire PPDU frame, which is composed of two parts: Preamble and Data. In this Chapter, the encoding block, which is related to the generation of the PPDU data, has been modified to evaluate the candidates' performance.

According to the configuration defined for the PSDU, the modified block offers the choice between four-FECs: WLAN CC, WLAN LDPC,

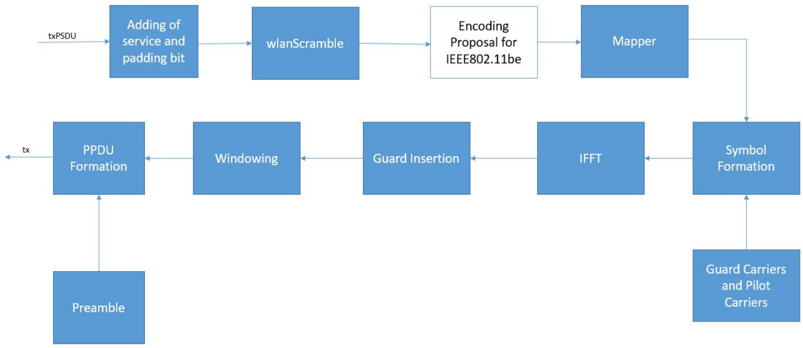


Figure 4.6: wlanWaveform structure.

LTE Turbo, and NR Polar. As shown in Figure 4.7, only the WLAN LDPC has a unique step in the encoding. In WLAN CC, a zero-bit sequence, defined tail bit sequence, is included in the data before the encoding. While concerning LTE Turbo, the encoded blocks have a code rate of 1/3, then a Rate Matcher block is added. This step is necessary for matching with the code rate defined in MCS. Finally, in NR Polar, the PSDU is concatenated with a CRC bit sequence before the encoding. Then, the obtained block passes to a Rate Matcher for the obtainment of the MCS code rate.

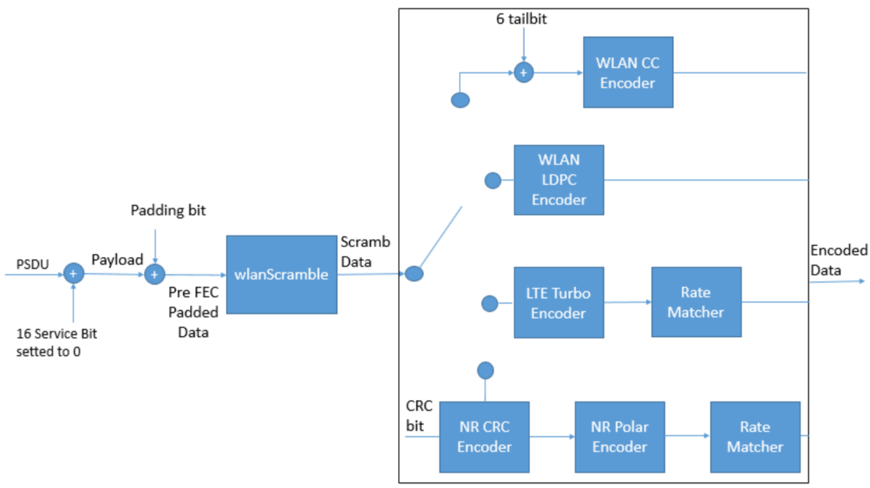


Figure 4.7: Modified block for studying the channel codes for IEEE 802.11be.

4.5.3.2 Data Bit Recover Block

The Data Bit Recover (Figure 4.8) recovers the PSDU from the OFDM symbols reserved for the data. This process consists of four main steps: demapping, decoding, descrambling, and removing the additional bits. Among these steps, this Chapter proposes an adaptation of the IEEE 802.11 decoding block to analyze the FECs, as shown in Figure 4.9.

The changes applied to the decoding block allow the decoding of the candidate FECs. There are additional steps in the decoding for the WLAN CC, NR Polar, and LTE Turbo. In the case of WLAN CC, there is the padding bits removal after the decoding. In LTE Turbo, before the decoding, the blocks pass to a demapper block for matching with the decoder requirements. Finally, 5G NR Polar before the decoding has a Rate Recover step, while, after the decoding, there is the CRC Removal applied to the decoded block.

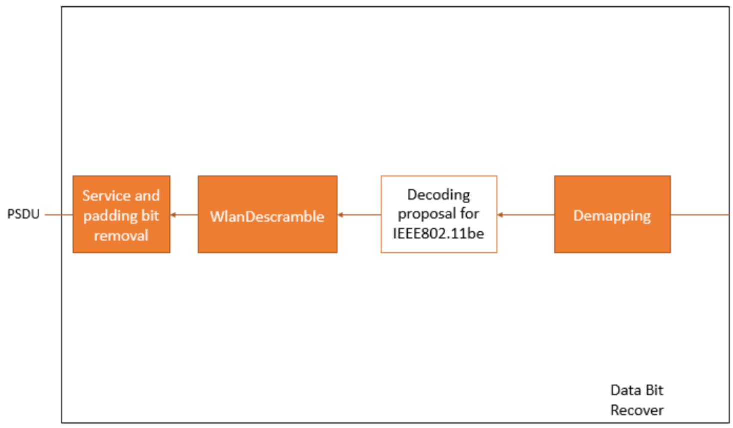


Figure 4.8: Data bit recover structure.

4.5.4 System Model Parameters

Table 4.8 summarizes the parameters used for the simulations. Regarding the data transmission within FA environments, these are the following configurations. Concerning PSDU, the adopted lengths are 32 B and 64 B, while regarding the MCS options, MCS0 and MCS1 have been chosen due to being the most robust configurations in IEEE 802.11 [16]. Both MCS present code rates 1/2, while the modulation

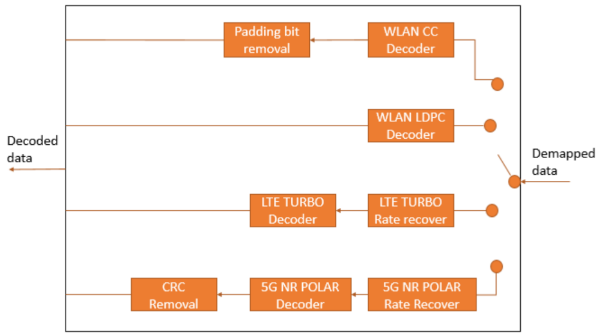


Figure 4.9: Proposed decoding structure.

used are BPSK for MCS0 and QPSK in the case of MCS1. Regarding the simulation setup, the following parameters have been adopted: the transmission of 10^5 frames per point, BLER threshold of 10^{-3}, and, finally, a simulation step between points of 0.25 db.

The values of PER shown in Table 3.2 represent the desired reliability at the MAC layer, where, in addition to the effect of channel coding, there is the effect of the MAC layer techniques, such as the spatial retransmission techniques [13].

Table 4.8: Simulation parameters for WLAN platform.

Parameters	**Values**
PSDU Lengths [B]	32, 64
Modulation	QPSK, BPSK
Code Rate	1/2
Channel Models	AWGN, Scenario 7, CM8
Channel Parameters (AWGN is not included)	Mean = 0 dB, σ = 6 dB
BLER threshold	10^{-3}
Transmitted Frames	10^{5}
SNR steps [dB]	0.25

4.6 Practical Application Results

The section is composed of three parts. The first presents and discusses simulation results for an AWGN channel, the second discusses results for the Scenario 7 channel, and, finally, the third gathers the plots for the CM8.

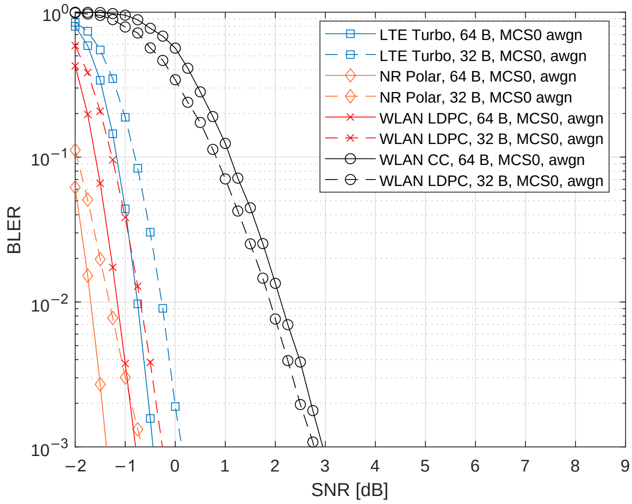
Industrial channel models such as Scenario 7 and CM8 help evaluate the performance of the IEEE 802.11be PHY layer under NLOS conditions in industrial environments. The results obtained by using different FECs can provide valuable insights into the potential performance benefits of each approach. Consequently, different future directions of the IEEE 802.11be standard could be addressed.

4.6.1 AWGN Results

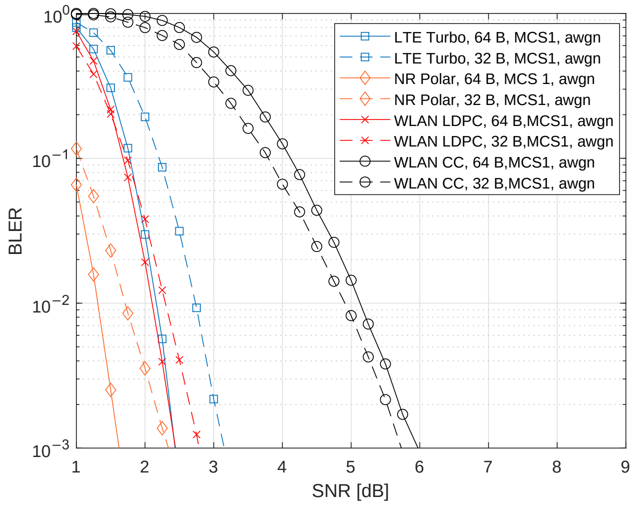
Figure 4.10a gathers the results for MCS0, while Figure 4.10b includes those for MCS1. As observed in both figures, the first noticeable result is that the 5G NR Polar provides the best performance. In MCS0, they reach -1.5 dB per payload for PSDU of 64 B, while -0.6 dB for PSDU of 32 B. One other result observed in both figures is the WLAN CC behavior. The PSDU 32 B case offers noticeably better performance than the case with 64 B. An improvement close to 0.2 dB occurs. The presence of tail biting explains this, as shown in Equation 4.1

Comparing the results for MCS0, WLAN LDPC offers very similar performance to 5G NR Polar. For both PSDU lengths, WLAN LDPC performs worst with a distance of 0.5 dB. In contrast, LTE Turbo distances itself by values close to 1 dB for 32 B, while, for 64 B, it is close to 0.5 dB. Finally, WLAN CC performs the worst. The distance to 5G NR Polar is close to 4 dB.

In the MCS1 case, WLAN LDPC and LTE TURBO provide a similar SNR value for 64 B, differencing of 1 dB respect the 5G NR Polar performance, while, for 32 B, WLAN LDPC is 0.5 dB away from 5G NR Polar, and LTE Turbo is 1 dB away. Finally, WLAN CC obtained the desired PER at almost 4 dB from the best-analyzed performance.



(a) MCS0 Results



(b) MCS1 Results

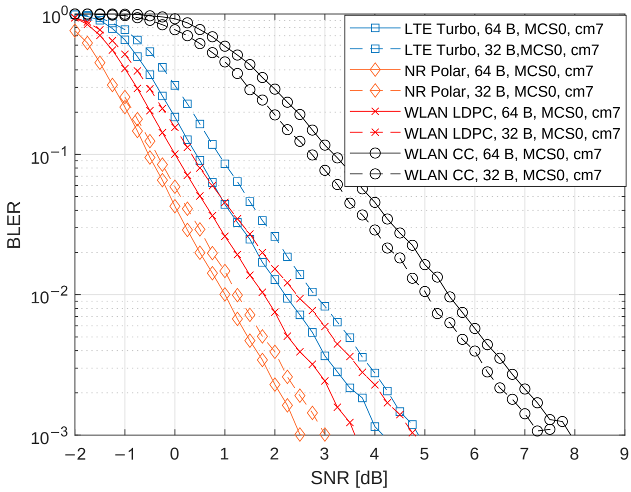
Figure 4.10: Comparison of the different FECs for AWGN channel.

4.6.2 Scenario 7 Results

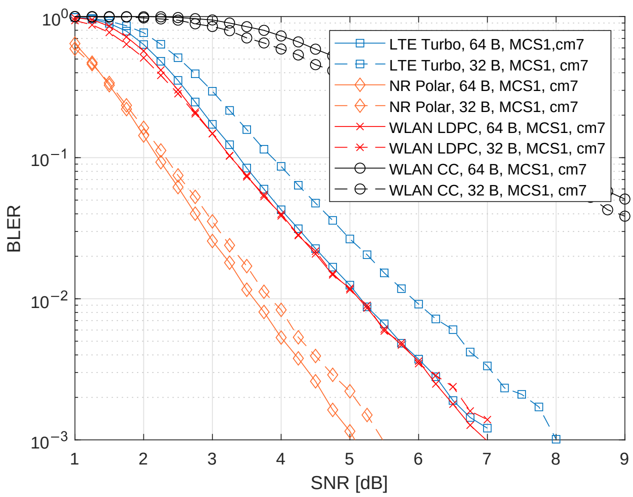
Figure 4.11a,b show the results for MCS0 and MCS1, respectively. Comparing the results with Figure 4.10a,b, it is notable that results are worse for all the cases. In MCS0, 5G NR Polar are shifted to the right by about 4dB, as WLAN LDPC and LTE, while WLAN CC is about 5 dB worse. The trend is similar to the MC1 case.

For the MCS0, 5G NR Polar provides 2.5 dB for 64 B and 3 dB for 32 B. WLAN LDPC varies between 3.5 dB and 5 dB, respectively, for 64 B and 32 B. LTE Turbo varies between 4 dB and 5 dB. For WLAN CC, the SNR values are above 7 dB.

Regarding the MCS1, the 5G NR Polar performances for both the PSDU lengths reached values around 5 dB, while, in the case of WLAN LDPC, they pass around 7 dB. In the LTE Turbo simulations, the performance reached 7 dB and 8 dB, respectively, for 64 B and 32 B. Finally, for WLAN CC cases, the desired threshold is achievable for values higher than 9 dB.



(a) MCS0 Results

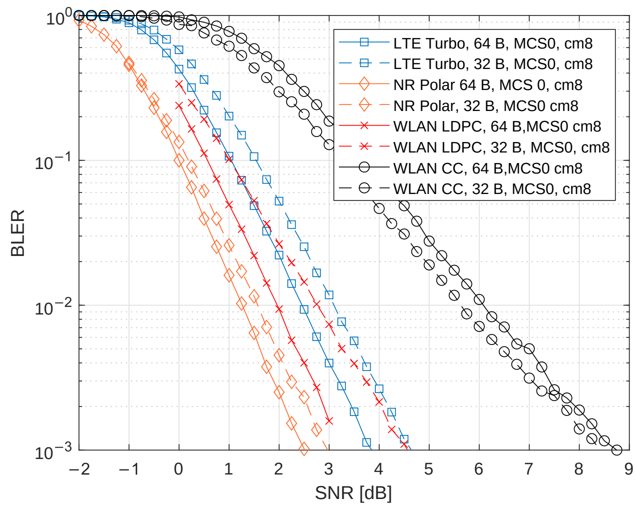


(b) MCS1 Results

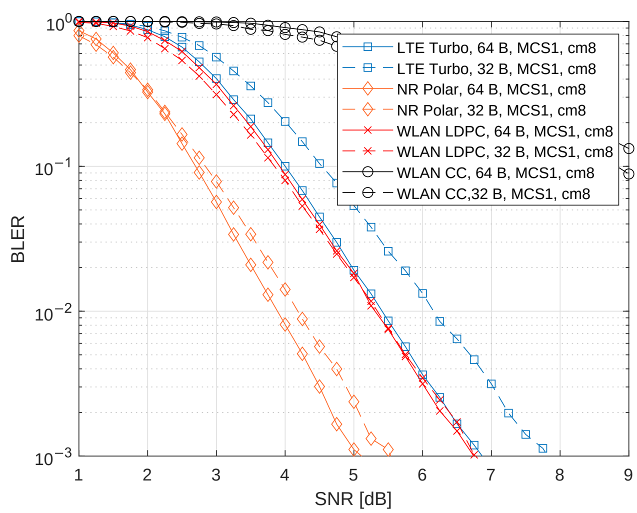
Figure 4.11: Comparison of the different FECs for Scenario 7 channel.

4.6.3 CM8 Results

In Figure 4.12a,b, the results for the MCS0 and MCS1 cases are presented, respectively. Compared to the AWGN case, the channel performance degradation is comparable to the Scenario 7 case, with a 4-5 dB deterioration (see Section 4.6.2). Similarly, 5G NR Polar outperforms the other candidates for all the proposed configurations, while WLAN CC performs the worst. For the MCS0, 5G NR Polar reaches 2.5 dB and 3 dB, respectively, for the PSDU lengths 64 B and 32 B. Concerning MCS1, these performances pass to 5 dB and 5.5 dB. Regarding WLAN CC, the performances are close to 9 dB in the MCS0 configuration, while, for MCS1, such values are higher than 9 dB.



(a) MCS0 Results



(b) MCS1 Results

Figure 4.12: Comparison of the different FECs for CM8 channel.

4.7 Summary

The study presented in this Chapter is composed of two parts. The first part describes a comparative analysis among FEC candidates for Industrial Wireless Communications in reliability and latency terms. The choice results from the conclusions from the state-of-the-art proposed in Chapter 2. This preliminary step was necessary to detect a reduced number of candidates with high performance for short packet communications. The identified FEC candidates are QC-LDPC, POLAR, TBCC, and PCCC. In particular, in POLAR, CA-POLAR is considered, while LTE TURBO is for the case of PCCC.

The reliability analysis is provided by a BCM toolkit developed with MATLAB. On the contrary, the latency has been evaluated in terms of decoding latency. This metric is associated with a decoding algorithm and has been estimated considering the results in trade publications. Also, decoding algorithms have been considered for short-packet communications. Each FEC candidate is combined with the algorithm that provides the best performance regarding reliability and latency. The suggested combinations are BP for QC-LDPC, SCL for CA-POLAR, WAVA for TBCC, and Log-MAP for LTE TURBO.

The results show that QC-LDPC and CA-POLAR suit the FA requirements. In particular, QC-LDPC is a potential candidate for critical communications, while CA-POLAR is for safety communications.

The second part of this study proposes a methodology for reliability analysis for industrial scenarios. The methodology proposes a WLAN PHY model toolkit, which simulates the communications between two IEEE 802.11be nodes. The channel models are CM8 and Scenario 7 and represent industrial environments.

This analysis compares the performance of LTE Turbo and 5G NR Polar with the FECs provided in the IEEE 802.11be standard: WLAN LDPC and WLAN CC.

5G NR Polar, in particular, appears as the best one in the BLER versus SNR plots. In addition, there is an analysis of the decoding latency of these two candidates. Indeed, latency is a demanding requirement in FA use cases. Concerning this study, WLAN LDPC is the fastest due to its full-parallel decoding property.

The main conclusion is that the LDPC codes designed for the IEEE 802.11 standards show suitable performance for being applied within IEEE 802.11be in FA scenarios. For this reason, IEEE 802.11be does not require changes to adopted FECs. However, on the other hand, 5G NR Polar needs to be considered for its performance in future application scenarios within IEEE 802.11be, particularly for communications that require data sizes smaller than 32 B.

Chapter 5

Deterministic Medium Access Approaches for Wireless in Industry

5.1 Introduction

This Chapter includes a proposal for the use cases in the Critical communications field. The application is suggested for high-density networks. The challenge of real-time communication among robots in warehouses has been considered a use case (Smart Warehouses).

Conventional wireless communications are not designed to provide the demanding performance to monitor and control factory processes. The optimization of the layers is one solution for this challenge. In the last decade, optimized versions for IEEE 802.11, IEEE 802.15.4, and 5G NR have been proposed to cope with these new applications. These proposals are based on modifications of the MAC and PHY layers. Nowadays, these solutions only partially fulfill the Factory Automation use cases. Besides the technological lack of widespread wireless standards, another challenge is associated with the industrial environment. Indeed, there are multiple obstacles between the AP and the nodes. The selective frequency fading and slow channel time variations typical of these models make the deterministic communications based on the time domain diversity commonly inefficient [12, 13], especially if multiple connectivities between devices are required, as in the case of Smart Warehouses.

One solution for this scenario could be IEEE 802.11ax. The reasons are the following. First, it introduces OFDMA. Second, compared to the previous IEEE 802.11 standards, ax provides more data subcarriers per channel. These novelties address IEEE 802 towards multi-user communications, allowing the connection of several users in a single transmission [195]. Moreover, on the one hand, in [122], OFDMA is considered to achieve low latency with a high density of interconnected nodes in critical scenarios. On the other hand, it also shows robustness against frequency selective fading, typical for industrial environments. Indeed, it could be operated for communications based on exploiting frequency diversity, which improves the reliability for these scenarios.

Due to its potential to meet the requirements for the use cases, this chapter proposes different optimizations for the PHY and MAC layers of IEEE 802.11ax.

The study is structured as follows. First, a background of the smart warehouses is given, highlighting the different issues related to the design of ad-hoc wireless systems. This part terminates by suggesting IEEE 802.11ax with OFDMA as a potential solution. Then, the proposal is defined. This architecture includes the definition of the network topology, PHY layer optimization for latency purposes, and deterministic MAC layer algorithms to improve the reliability and latency performance of the system. The algorithms propose frequency diversity when a retransmission is required. Finally, the chapter proposes reliability and latency analysis. The toolbox comprises MATLAB and OMNET++ modules and evaluates the reliability performance at the MAC layer with different industrial channel models. The latency is provided in the form of superframe duration via MATLAB analysis.

5.2 Wireless Systems for Smart Warehouses: a comprehensive Background

Industrial communications for manufacturing are classically grouped into Safety, Critical, and Non-Critical Communications. Critical communications are further classified into Open-loop and Closed-loop Controls. Indeed, the scope of these two groups is similar as both are considered for managing the devices and machinery involved in the manufacturing processes, avoiding any damage to machinery, processes, and operators.

The first group is directed to prevent any risk of damaging equipment or process interruption and personnel safety. In this case, the use cases require demanding performance in terms of latency, reliability, and connected devices. The second group includes the monitoring operations that, due to their nature, are not associated with the risks previously mentioned.

Therefore, Critical Communications include many use cases that still need to be fulfilled by the forthcoming wireless systems proposals. Among these, smart warehouses result in an attractive use case for critical communications requiring high-reliability communications for numerous devices, considering latencies in the millisecond. This section offers a background of the mentioned use case, which provides the description of the scenario, and the associated issues. Finally, a potential solution is also introduced.

5.2.1 Smart Warehouse Use Case

Industry 4.0 has introduced the need to automate manufacturing processes by incorporating the most modern technologies. Among these, a recent trend is substituting human tasks with automated robots. An example of a use case is the deployment of AGVs and AMRs for controlling and monitoring warehouse processes. These robots must share relevant information for the processes' continuity and safety in real-time. On the one hand, these robots manage the whole logistic process, and when necessary, they help with the equipment movement from the warehouse to the workshops for production. On the other

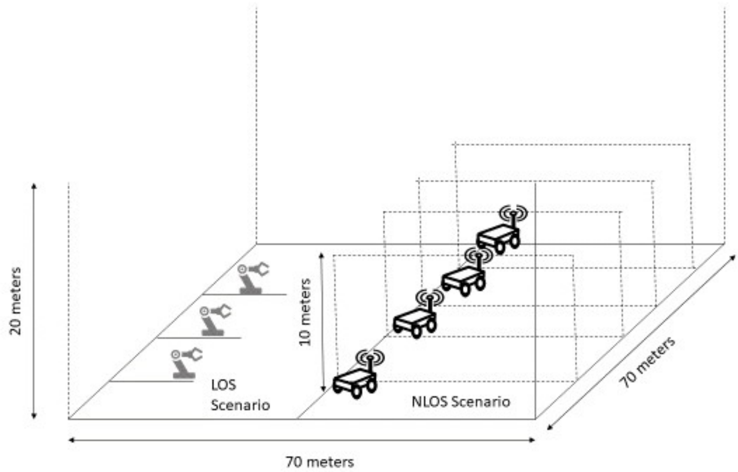


Figure 5.1: Use Case Layout

hand, safety might take a relevant role also in many of those scenarios.

A layout for Warehouses is depicted in Figure 5.1. It consists of two different areas: distribution and storage area. The distribution area is operated to move products from the workshops to the storage area. This task requires cranes, AGVs, AMRs, assembly lines, and conveyor belts for packing and transporting products or materials. Then, the storage area is the zone where the products are stocked. A high density of heightened racks characterizes it. In this case, AGVs or AGVs with AMRs are adopted for transportation and storage operations.

Considering the properties of the field trials' environment in [14] and the descriptions in [141, 196], a potential warehouse environment for the use case can be described as follows.

The building dimensions are 70 m x 70 m x 20 m, and metallic structures predominate in walls and ceilings. Five meters below the ceiling there are also metallic objects like pipelines, video surveyllance structures, and lighting. For illustrative purposes, we will assume that the proposed scenario could be used to store metallic pieces for the automotive industry. The distribution area does not present a high density of metallic materials, as it occurs for storage. Regarding the network configuration, each robot has a proper STA required for network communications. Moreover, the APs are installed at a predominant height to simplify the Line-of-Sigth during communications.

This network requires different channel models for characterizing the difference in propagation features associated with each. The density of metallic materials could help in this hypothesis. First, the distribution area does not present a high density of metallic objects and is considered a Line-of-Sight (LOS) scenario. On the contrary, the high density of racks assumed to be 10 meters in height interrupts the line-of-sight among the connected nodes. As a consequence, this scenario is regarded as Non-Line-of-Sight (NLOS).

Robot cooperation is required to complete the warehouse tasks. The risk of process interruption or human safety must be also taken into account. Therefore, the network must provide highly accurate and precise communications. For this reason, AGVs and ARMs are equipped with different sensors for obtaining information like position, presence of obstacles or humans, and inventories. These sensors could acquire this data through cameras or lasers. The second solution is recommended for the proposed application.

Finally, these requirements could be represented with the following KPIs. First, this cooperative scenario requires networks that achieve 1 ms or below latencies, as defined in [197]. The ETSI guidelines [7] help define the robot density, which considers 0.1 robots per m^2. Therefore, the presence of 32 devices among AGVs and AMRs within the warehouse is reasonable in this proposal. Finally, the network must be able to control and monitor these robots. A secondary element for this proposal is the absence of human operators in the environment. Therefore an error rate $\leq 10^{-6}$ is considered acceptable for the simulations. Table 1 summarizes the system's KPIs.

5.2.2 Industrial Channel Models

Factories are traditionally characterized by the high density of static metallic pieces, some moving machines, and both static and moving operators. These elements have an impact on channel propagation as follows. First, particularly high coherence times, if compared with the symbol times of most wireless PHY designs. Second, the presence of

Table 5.1: KPIs for Smart Warehouse

Use Case	PER	Latency [ms]	Payload [B]	Device Density
Smart Warehouse	$\leq 10e^{-6}$	≤ 1	≤ 40	$\simeq 0.1\, m^2$

frequency selective fading. These effects may cause a slow variation in time of the industrial channels that make time-domain retransmissions inefficient [12–14].

Nowadays, there is a reduced number of channel models for industrial communications. They are considered excessively generic or outdated, dating back to the 2000s [12–14]. Two of the most widespread industrial channel models encountered in the literature were introduced in 2004 as the IEEE 802.15.4a channel studies, based on the report by Molisch *et al.* [141] and the measurement campaign results from [14]. CM7 represents industrial LOS scenarios, whereas CM8 addresses industrial NLOS links. Both CM7 and CM8 are based on the Saleh-Valenzuela model. These models' main concern is their applicability to specific analysis scenarios. Indeed, their validity is only confirmed for a maximum distance of 8 meters. Nevertheless, due to the lack of alternatives, these channels are used for the analysis proposed in this paper.

5.2.3 Discussion on Design Issues

Numerous aspects must be taken into account to fulfill the KPIs required by the use case of the smart warehouse. Based on the background analysis, the authors highlight two major aspects.

5.2.3.1 Limits of the current Wireless Systems

Wireless solutions have been proposed over the last decade for similar analysis scenarios. Most of them are still far from fulfilling multi-node transmissions in the order of the millisecond or less. An example is given by WIA-FA and 5G NR, which are designed for providing superframe durations above 1 ms. Another one is the IEEE 802.11 standards, which provide large waveforms at the PHY layer on the one hand, whereas on the other, the MAC layer traditionally adopts CSMA/CA. Nevertheless, some guidelines provided by [121, 122] suggest different aspects that the wireless systems must provide within warehouses. At the PHY layer, optimized preambles are required to reduce latency. On the other hand, at the MAC layer, using deterministic protocols combined with OFDMA could help achieve the requirements for both reliability and the number of devices.

5.2.3.2 Channel Effects

The Industrial Channel Models proposed in the literature show a common behavior concerning high coherence times and frequency selective fading. These effects could obstruct the desired reliability as highlighted in previous works as [12, 14]. As a consequence, the latency is also affected. The main reason is given by the potentially high number of required retransmissions. Therefore retransmissions based only on the time domain are unreliable for guaranteeing the expected PLR. One solution is the use of retransmissions on the frequency/space domain. OFDMA could be helpful for this goal by subgrouping OFDM channel resources into different subchannels. Indeed, due to the frequency of selective fading and the high coherence time of the channel model, each sub-channel has a proper time variation. This condition is obtained if, simultaneously, the coherence time of the channel is larger than the symbol time and the signal bandwidth is higher than the coherence bandwidth of the channel model [198]. Therefore the subchannel re-assignation could introduce benefits regarding reliability.

5.2.4 A possible solution: optimized IEEE 802.11ax for Smart Warehouses

The emerging need to transmit various types of information is one of the drivers of the IEEE 802.11ax development, which handles interferences between devices, includes tools against frequency selective fading, and provides heterogeneous QoS connections. Some relevant specific novelties include higher rates per subcarrier per OFDM symbol and OFDMA for multiuser communications. The first feature is obtained by reducing the subcarrier spacing. Indeed, in the previous IEEE 802.11

standards, this parameter was four times larger than IEEE 802.11 ax, and as a consequence, the current OFDM symbol is four times longer. Then, OFDMA, in line with other 3GPP standards, provides a tool for multiuser communications.

In IEEE 802.11ax, OFDMA can be used to transmit short data and consists of grouping the adjacent subcarriers that compose a channel into resource units (RUs), considerably as sub-channels. Depending on the network requirements, this grouping could be heterogenous or not. Therefore, in high bandwidths, such as 160 MHz, this approach allows sending short data for many users without worsening the data rate [16, 195]. To face the issues of synchronization for the uplink, IEEE 802.11ax introduces the Trigger Frame. The AP sends this control message to coordinate the uplink communication. These novelties increase the capacity of IEEE 802.11ax, allowing it to include a maximum of 74 users in a 160 MHz channel [16].

5.3 Optimizations

This section introduces some optimization mechanishm for IEEE 802.11ax to adress the KPI identified in the proposed warehouse scenario. All the proposals are based on the comprehensive analysis described in Section II. First, the network topology is briefly introduced, and then, the proposals for PHY and MAC layers are described in detail.

5.3.1 Network Topology

In this use case, IEEE 802.11ax must monitor and control the numerous robots involved in the warehouse processes. Due to the strict latency requirements, it is modeled as a star topology. The following elements compose the setup. First, the Remote Controller is included for management purposes. Indeed, it configures, monitors, and controls the whole network and sends such information to the APs through a real-time ethernet protocol.

Then, the APs coordinate the data exchange between the Remote Control and the rest of the nodes (or STAs), organizing the different periods that occurred in a superframe. Their main functions are the following:

1. Start the processes.
2. Report data to the Remote Control.
3. End of the processes.
4. Signalization of any critical event to the Remote Control.

Critical events are circumstances that affect or obstruct the state of the processes. AP is connected via wired protocols with the Remote Control, whereas the communication with the node is wireless. Finally, the nodes, which include sensors and similar or equivalent devices, send diagnostic data and alarms for the rest of the network and receive configuration, management, and command information.

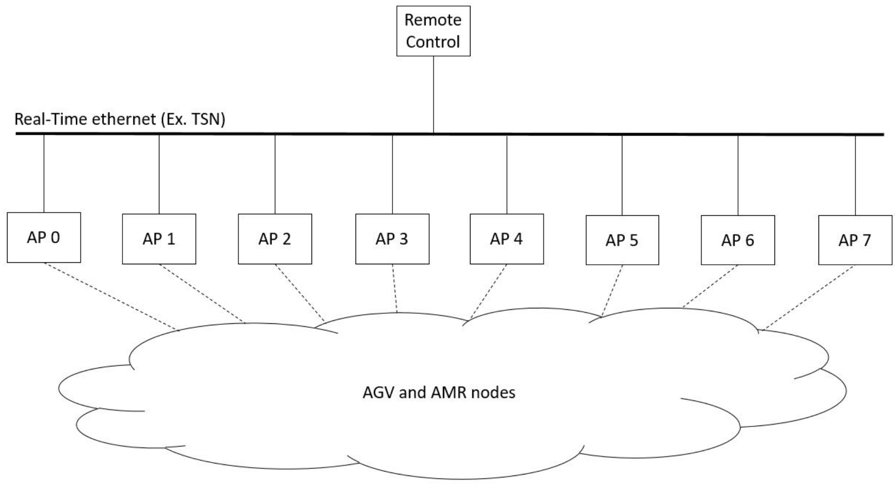


Figure 5.2: Network topology representation

5.3.2 Optimized PHY Layer

In most IEEE 802.11 standards, the PHY waveform comprises multiple types of OFDM symbols. These include the preamble, which is required for data detection, and the messages carrying the actual information. Traditionally, the preamble length on the PHY layer is a negligible fraction of the required total time for transmitting the packets. Nevertheless, its overhead is not negligible for short-packet transmission. Therefore, its dimension must be as small as possible to get low latencies. First, in IEEE 802.11ax, the preamble is composed of two parts. The first allows backward compatibility with previous 802.11 standards, with a structure similar to IEEE 802.11a/g. The other part provides the IEEE 802.11ax functionalities and can only be decoded by IEEE 802.11ax devices. Second, the relatively slow time variation of the industrial channels has also to be taken into account in this preamble optimization [11, 122]. Indeed, direct channel estimation from AP could be optional in these environments due to slow channel variations, and therefore, it could be measured by the STAs during the DownLink period (DL). This property also helps reduce the preamble structure and the latency as a consequence. For this reason, this proposal follows the guidelines of the previous works [11, 122]. Respect these, here is the proposed optimization of the *ax* preambles for faster

OFDMA communications.

For this reason, different waveforms are considered with extended preambles required by the AP. In this case, the legacy preamble composed by L-STF and L-LTF, as provided in IEEE 802.11ax, is used to give the STAs the required information for channel estimation. For both, the duration is $8\ \mu s$. Moreover, two additional symbols are included for more detailed user information. The optimized HE-SIG A defines Bandwith and the frame period (DL or UL) [16]. Concerning the standard design, this proposal only requires one symbol. At the same time, the optimized HE-SIG B offers information for decoding and the presence or not of retransmissions during the frame period and, for this purpose, only requires one symbol [16]. These optimized versions show a duration of $4\ \mu s$.

Due to the slow channel variation, the STA waveform is shorter. Its preamble must contain detection information for the AP only. Therefore, considering the IEEE 802.11ax standard, a reasonable option is a preamble comprised exclusively by RL-SIG [16]. Each sub-channel corresponds to a proper RL-SIG that allows simultaneous data transmissions for uplink. Its duration is $4\ \mu s$

The data duration respects IEEE 802.11ax guidelines and is obtained as a multiple of the OFDM symbol time (T_{OFDM}).

$$\begin{aligned} T_{Data} &= T_{OFDM} \cdot N_{OFDMSymb} \\ N_{OFDMSymb} &= \lceil \frac{S_{bit} + P_{bit} + 8 \cdot (Data + Overhead)}{NSD \cdot NBPSCS \cdot NSS \cdot R} \rceil \end{aligned} \tag{5.1}$$

S_{bit} and P_{bit} correspond to the service and the padding bit defined at the MAC layer. NSD is the number of data bits per subcarrier. $NBPSC$ corresponds to the number of bits necessary for the subcarrier transmission, depending on the MCS. NSS is the number of spatial streams. Finally, R is the code rate, which also depends on MCS.

5.3.3 Modified Control Frames

In this subsection, the different control frames are here introduced to achieve higher reliability, reduced latency, and service a multiuser environment.

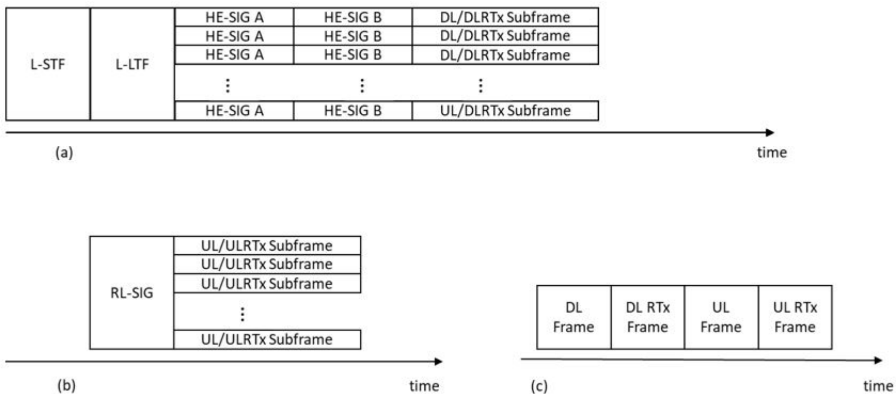


Figure 5.3: Optimized (a) Downlink and (b) Uplink frames for IEEE 802.11ax. (c) Superframe structure

First, following the concept proposed in [26], the beacon allows the clock synchronization between AP and STAs. For this reason, this message includes a timestamp for synchronizing communications, the superframe duration, and the bandwidth. Second, the Trigger Frame operates as a scheduler between AP and STAs [16, 197]. Due to the channel assumptions and the beacon structure, this proposal only contains MCS, RU allocation for each STA and the UL duration. Finally, the STA sends these data during eventual retransmission periods to allow synchronization.

5.3.4 Optimized MAC layer

The latency requirements imposed by the Warehouse use case do not allow the implementation the traditional IEEE 802.11 MAC layer based on CSMA/CA. For this reason, the following proposals are based on deterministic communications, where a pre-established superframe is composed by downlink and uplink periods, including retransmissions. Figure 5.3 depicts the superframe structure. The following methodologies exploit OFDMA for offering two retransmission schemes based on the frequency domain.

5.3.4.1 Methodology I

The MAC layer combines the properties of the TDMA medium access technique to guarantee deterministic frame delivery with a periodic RU re-allocation for facing the slow time variation of the industrial channels. Each $\delta\tau$ the Remote Control changes the RUs for each STAs, which is pre-established for the network configuration. τ is defined based on the channel model properties. The AP receives the ID of the required nodes from the Remote Control, which also establishes the length of the superframe. The communications are initialized in the DL period. Here AP sends the following typologies of messages. Start or Stop for their processes, Alarms in the case of risks, and data reports obtained by STAs. These also include channel estimation.

The DL starts with the resource allocation procedure, where each node is associated with a specific RU. Every $\delta\tau$, a RU re-assignation occurs. The period finishes when the ACKs are received from each STA. Otherwise, AP changes from DL to DL RTx period. The rest of the nodes, which do not require retransmissions, will send empty data frames during this period.

The UL starts with a trigger frame sent by the AP for the involved nodes. Three message typologies are considered. Data Reports obtained by measurements. Second, signalization if the process is finished. Finally, Alarms when a risk is detected. The period finishes when the data is received. Otherwise, AP changes from UL to UL- RTx period. The nodes which not require retransmissions will send empty data frames during this period. Algorithm 5.1 represents the described methodology during a superframe.

5.3.4.2 Methodology II

This subsection describes the purpose of combining the deterministic frame delivery with the RUs re-allocation in the case of erroneous detections. The frequency selective fading and slow time variation of the channel allows for considering OFDMA as the union of different time-varying channels. The main idea is piggybacking the best sub-channels in the retransmissions. STAs give the channel estimations to the AP in the form of diagnostic messages (or data reports). These

Algorithm 5.1 Methodology I

Define: DL/UL. Variable for period selection;
Define: STA_i, RU_i. ▷ STA defines the node ID, while RU defines the subchannel ID;
Define: t, τ, k. τ ▷ temporal variables required for resource reallocation
Step 1 - Initialization
$DL/UL \leftarrow 1$ ▷ If DL/UL is set to 1 is downlink.
Step 2 - Resource Allocation
if $t = k\tau$ **then**
  if k is even **then**
    $STA_i \leftarrow RU_i$
  else if k is odd **then**
    $STA_i \leftarrow RU_{max-i}$
  end if
end if
  Define: ACK_i ▷ ACK associated to STA_i.
Step 3 - ACK Detection for Data:
if ACK is received **then**
  $ACK_i = 1$
else
  $ACK_i = 0$
end if
if All $(ACK_i = 1)$ **then**
  Move to **Step 4** ▷ The Message has been detected, then Superframe passes to the Downlink/Uplink Period
  if DL/UL=1 **then**
    $DL/UL \leftarrow 0$ ▷ The Superframe passes to Uplink
  else
    $DL/UL \leftarrow 1$ ▷ The Superframe passes to Downlink
  end if
else
  Move to **Step 4** for Retransmission
end if
Step 4 - Retransmission
if DL/UL=1 **then**
  Move to **Step 2**
else
  Move to **Step 3**
end if

messages are then forwarded to the Remote Controller, which serves as a database, storing the channel estimations of each STA, which are identified by a unique STA ID. The AP uses this database to reassign RUs based on the following approach: STAs requiring retransmissions are assigned to the better sub-channels, while the others are reassigned to the worst. The reassignment process is ordered according to the STA IDs, which could be ascending or decreasing.

The scheme operates as follows. The AP receives the ID of the required nodes from the Remote Control, which also establishes the length of the superframe. The communications are initialized in the DL period. Here AP sends the following message types.

1. Start and stop messages individually sent to the devices involved in specific processes.
2. Alarms if the devices detect any risk event. These messages are used for arresting the eventual operations.
3. The request for data reports.These are the results of device measurements reported to the STAs or the channel estimation. Indeed, each STA retains many sensors to monitor and control the processes.

The DL starts with the resource allocation, where each node is associated with a specific RU. A beacon frame is included in the data transmission and retransmission for achieving synchronism. If the communication fails, the AP will reallocate the resources during the RTx Period. The period finishes when an ACK is received. Otherwise, AP changes from DL to DL- RTx period. The STAs that do not require retransmissions will send empty data frames during this period and reallocate in different RUs.

The UL starts with a trigger frame sent by the AP for the involved nodes. Here the nodes could send three kinds of messages:

1. Data Reports, which contain channel estimation or measurements.
2. Signalization when the process terminates.

Algorithm 5.2 Methodology II

Define: DL/UL. Variable for period selection;
Define: STA_i, RU_i. ▷ STA defines the node ID, while RU defines the subchannel ID;
Step 1 -Resource Allocation
$STA_i \leftarrow RU_i$
Step 2 - Downlink/Uplink Period
if ACK is received **then**
  $ACK_i = 1$
else
  $ACK_i = 0$
end if
if All $ACK_i = 1$ **then**
  if DL/UL=1 **then**
    $DL/UL \leftarrow 0$ ▷ Superframe Passes to Uplink
    Move to **Step 2**
  else
    $DL/UL \leftarrow 1$ ▷ Superframe Passes to Downlink
    Move to **Step 2**
  end if
else
  Move to **Step 3**
end if
Step 3 - Resource Re-Allocation
The STAs with the worst channels pass to the best ones and viceversa.
Move to **Step 2** for retransmission

3. Alarms if the AGV or ARM detects any risk event.

The UL period finishes when the AP received the data. Otherwise, AP changes from UL to UL- RTx period. The nodes that do not require retransmissions will send empty data frames in a new RU during this period. The pseudo-algorithm during the superframe is proposed in Algorithm 5.2.

5.4 Reliability Analysis

This study aims to test the network reliability performance of the optimized IEEE 802.11ax MAC Layers solutions in Section III. These are compared with a retransmission scheme based only on the time domain. The simulation platform requires two software programs, Matlab2019b and OMNET++ 5.6.2. Matlab2019 b's purpose is twofold. First, the WLAN system toolbox has been used to implement the IEEE 802.11ax nodes transceiver chain under the industrial propagation channel conditions. This model does not include effects associated with the multipath. The preamble optimization proposed in Section II is not included here, as it does not have a relevant impact on the reliability performance of the PHY layer, as channel coding and MCS are the same as the IEEE 802.11ax legacy system. Then, the Communication system toolbox is used for the channel models, including the slow-fading effects.

OMNET++ 5.6.2 is the network simulator proposed for simulating the OFDMA transmission in industrial scenarios. For each node, the error rates are calculated as a function of the instantaneous SNR. The instantaneous SNR also includes the fading effects with the PHY layer performance. Moreover, frequency selectivity favours uncorrelation between the instantaneous SNR detected by each one of the nodes involved in the communication. This assumption allows defining the instantaneous SNR differently for each node. Indeed, the simulator estimates this parameter independently for each subchannel. A total bandwidth of 160 MHz has been considered for multi-user communications between the robots involved in the warehouse. Each RU contains 242 data subcarriers, providing resources for eight users on a single frame. The standard defines a minimum of 26 data subcarriers per RU. Nevertheless, the authors consider this configuration an assumption for maintaining the condition of selective frequency fading, as the subchannels could be shown a bandwidth lower than the coherence bandwidth of the models [198]. CM7 and CM8 are the propagation models selected for the proposed industrial scenarios. Indeed, their properties show a good match with the environments considered in this study. The CM7 (as a LOS channel) has been considered for the distribution area, whereas CM8 is appropriate for the storage.

Table 5.2: Simulation Parameters

Parameter	**Value**
BW	160 MHz
RU configuration	242
Time Guard	0.8 μ s
T_{OFDM}	12.8 μ s
Data Size	13 B
Superframe Duration	1 ms
Coherence Time	30 ms
Tx Power	10 dBm
Communication Range	8 m
LOS Channel	CM 7
NLOS Channel	CM 8
K-Factor	14
N Devices	32
Required APs	8
dB Step	1 dB

Then, the results are represented as curves of Error Rate vs. SNR. The error rates proposed are the following. The Packet Error Rate (PER) evaluates the error rate without retransmissions. TDMA represents the error rate with retransmission only in the time domain. Then, Methodology I shows the results for the first retransmission scheme in Section III, while Methodology II is associated with the second proposed methodology.

These curves represent the reliability of superframe transmissions with a duration of 1 ms, where UL and DL periods, as defined in Section III are included. MCS 1 is the modulation and coding scheme considered in this study. On the one hand, this configuration allows high reliability, which is essential for the use case. On the other, this setup offers a data rate of 17 Mbit/s, sufficient for transmitting the information obtained by the AGVs and AMRs during the processes. The channel models considered a distance of 8 meters between the APs and the nodes. Table 2 summarizes other the simulation parameters.

Figure 5.4 and 5.5 represent the CM7 and CM8 scenarios, respec-

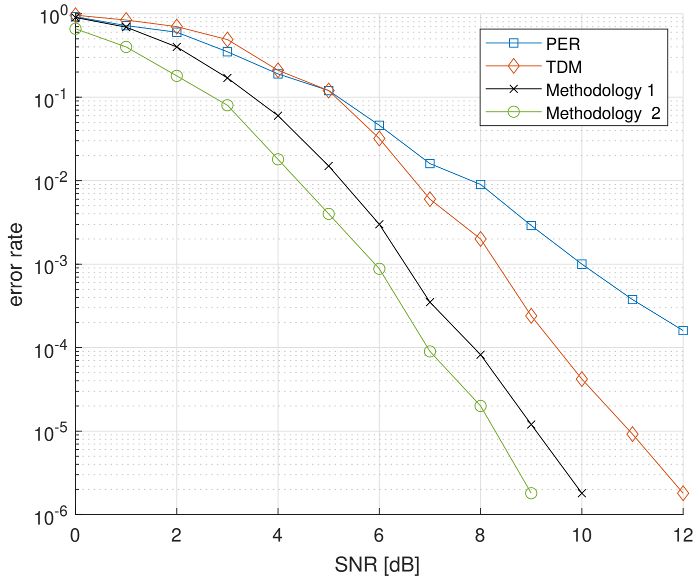


Figure 5.4: Reliability Results for CM7

tively. The performance comparisons are based on a packet error rate threshold of 10^{-6}, considered adequate for the studied use case [197].

As expected, Methodology II outperforms the other proposals in both scenarios as it exploits the frequency diversity. For the CM8 case, the proposal is 7 dB better than TDMA and 5 dB better than Methodology I. While in the CM7 scenario, due to the presence of Line-of-Sight, minor differences are shown in the performance for these retransmissions. In this case, Methodology II results in 3 dB gain when compared with TDMA and 1 dB gain agains Methodology I.

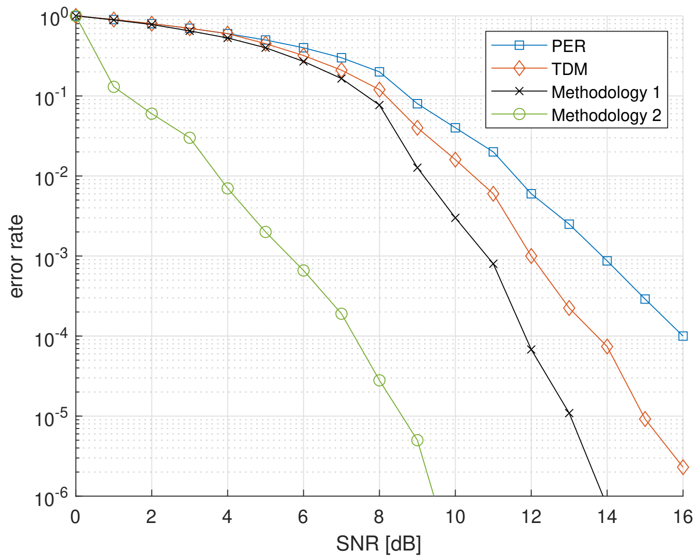


Figure 5.5: Reliability Results for CM8

5.5 Latency Analysis

Latency estimation is a critical research topic for Factory Automation. On the one hand, it is noticed that the current wireless systems solutions are designed for generic communications without strict latency requirements. Consequently, they show physical limits for achieving latencies below 1 ms, as demonstrated by well-known standards like 5G NR, IEEE 802 families, and WIA-FA [9, 10]. Nevertheless, some proposals based on IEEE 802.11, such as SHARP and WirelessHP, paved the way for these goals.

Conversely, latency estimation is not straightforward, as many elements must be accounted for precise measurements. Some examples are hardware aspects, the layer considered, the delay associated with the channel models, and the simulator in the case of simulations. Traditionally this metric is considered at the MAC layer and is referred to as the superframe duration. One way is estimating the required cycle times during a superframe for a certain number of nodes [17]. This metric has been proposed in [17] to demonstrate the submillisecond superframe obtainable with w-SHARP.

The latency analysis follows the methodology proposed in [17]. In this case, we compare the superframe structure proposed in Figure 2 with the results for the 160 MHz in [17]. Retransmissions are not considered in this case.

Now, the analysis passes to the description of the superframe parameters. The analysis considers the latency performance for the 160 MHz case. Due to the communications required by the use case [7], the data length is assumed to be 13 B, as is common in industrial communications, while QPSK 1/2 is selected for the following reasons. First, it is considered a reasonable compromise between reliability and latency. Second, it is assumed that robots use lasers to monitor all tasks [17]. OFDMA is configured as RU-242 to offer continuity with the analysis proposed in Section 5.4. As in [17], it is assumed a Short Interframe Space (SIFS) of $3.5\ \mu s$ for the passage from downlink to uplink period. The AP preamble is large $24\ \mu s$, whereas it is $4\ \mu s$ for the STAs. The guard interval is $0.8\ \mu s$.

Figure 5 represents the latency results in cycle times per number of nodes. The superframe duration is estimated from a minimum of 8-9 users, respectively, for IEEE 802.11ax and SHARP, to a maximum of 50 users. For the highest number of STAs involved in a superframe, both methodologies are slightly below $250\ \mu s$.

The proposal shows slightly lower latencies compared with SHARP. The reason is associated with the industrial channels used in this study that limit the destination of data subcarriers per RU. For example, the ax superframe for 32 nodes needs 50 μs less than SHARP. Moreover, the higher number of data subcarriers introduced in IEEE 802.11ax could further reduce the latencies per number of nodes, allowing a maximum of 74 users per frame. On the contrary, SHARP allows a maximum of 9 users per frame, as IEEE 802.11g/n uses a lower symbol time that reduces the number of data subcarriers per channel [16].

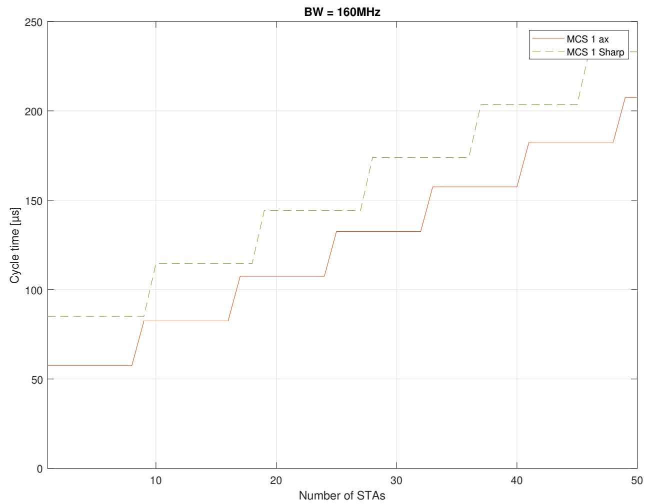


Figure 5.6: Latency per Number of STAs

5.6 Summary

This chapter proposes optimizations for IEEE 802.11ax, considering its potential application for managing AGVs and AMRs in storage processes for smart warehouses. Communications under the conditions in these scenarios must guarantee low latencies and high reliability to avoid process interruption and both goods and human safety risks when necessary. Indeed, the OFDMA capabilities introduced in this standard could help in facing the challenges of wireless system design for Factory Automation. On the one hand, some use cases require demanding KPIs that are difficult to be achieved with the current solutions. On the other hand, the industrial channel models severely downgrade the performance of these systems. Respect the previous IEEE 802.11 standards, IEEE 802.11 ax introduces a higher number of data subcarriers which is helpful in multi-user communications and is a potential solution for the frequency selective fading typical of the industrial channels.

This study proposes optimization for MAC and PHY layers, and their performance is evaluated through iterative simulations. Regarding the MAC Layer, two different deterministic schemes are proposed for achieving reduced latencies. Moreover, for reliability purposes, the approach provides retransmission schemes in the frequency domain that exhibit improved performance compared to the traditional TDMA method in industrial communications. The first methodology proposes a periodic re-allocation of the RUs. The second one, otherwise, proposes re-allocating the RUs for any erroneous packet in terms of the channel, offering the best performance in terms of reliability.

An optimization for the IEEE 802.11ax preambles for the PHY layer is proposed to solve the latency issues associated with IEEE 802.11ax. This scheme could be also considered for the future IEEE 802.11be. Also, the beacon and the trigger frame are optimized and limited for the latency goals. The main result is a sensible reduction of the number of symbols typically required by the IEEE 802.11ax waveform, which allows the achievement of latencies below 1 ms as required by the proposed use case. Moreover, this result has also been compared with w-SHARP, which proposes a Real-Time OFDMA superframe for IEEE 802.11n, showing similar performance due to the channel models used in this work. Indeed, IEEE 802.11ax offers a higher number of data subcarriers concerning SHARP, based on IEEE 802.11g/n. More users could be included in one IEEE 802.11ax transmission. IEEE 802.11ax permits a maximum of 74 users on a bandwidth of 160 MHz. In conclusion, the proposed optimizations for IEEE 802.11ax exhibit potential for industrial communications, particularly for URLLC with multi-user scenarios, like the smart warehouse use case.

Chapter 6

Conclusions

6.1 Introduction

This chapter summarizes the contributions of this thesis, the publications associated with the research activities, and several future research challenges.

6.2 Contributions

This thesis contributes to developing high-performance wireless systems for industrial communications. In particular, the vertical considered is Factory Automation. Indeed, the current wireless systems only partially fulfill the demanding performances required by its most critical use cases. For this goal, the three main contributions are proposed in this thesis.

The first contribution is the proposal of system parameters for defining the use cases for Factory Automation and metrics for evaluating the FECs' performance at the PHY layer. The second contribution consists of evaluating alternative FECs for industrial wireless systems. Finally, the last contribution is the proposal of an optimized IEEE 802.11ax for industrial applications.

6.2.1 Definition of system performance and metrics for the industrial wireless systesms for Factory Automation

In the second and third chapters of this thesis, after analyzing the system parameters and metrics for evaluating the industrial wireless systems, the significant contributions have been the definition of the Fields of Application and metrics for the FECs performance. The reasons for this contribution are the followings. On the one hand, the multiple visions for the definition of Factory Automation required a break-even point to better address the future challenges for Factory Automation. On the other hand, a methodology for the FEC evaluation of industrial wireless systems for Factory Automation is required. Indeed, these techniques impact the performances of these systems, in particular for reliability and latency.

Chapter 2 includes the study of the different guidelines for defining the use cases. Two main aspects have been highlighted. First, there are multiple opinions on the use cases definition for Factory Automation. In addition, the parameter values of many of these visions seem unjustified, as any theoretical proof has been included. Second, the guidelines focus mainly on the MAC layer. Nevertheless, the demanding perfor-

Table 6.1: Use Case visions for Factory Automation: A comparative between technical manuals and this contribution

Candidate	Lack of Empirical Studies	Focused on Factory Automation	Valid for Future Applications
ISA	Yes	Yes	No
Candel et al.	Yes	Yes	No
ETSI	Yes	Yes	Yes
NIST	No	No	No
Cavalcanti et al.	Yes	Yes	Yes
This Proposal	**No**	**Yes**	**Yes**

mance also needs a detailed analysis of the PHY layer.

As a result, Chapter 3 proposes a unified vision for the use cases, defining the Fields of Applications as observable in Table 6.1. Moreover, this chapter provides PHY layer metrics for analyzing and comparing the FEC techniques for reliability and latency.

6.2.2 Analysis and proposal of channel coding techniques (FEC) for industrial wireless communications

Chapters 2 and 4 analyze and compare numerous FEC techniques for short-packet communications for industrial wireless systems. Moreover, Chapter 3 highlights the importance of conducting more studies to investigate the application of FEC in short-packet communications. While FECs are widely applied for long data packets, their effectiveness in correcting errors in short packets needs to be better understood. The main contribution is the suggestion of candidates, which are compared in terms of latency and reliability.

Chapter 2 provides a taxonomy of FEC for short-packet communications, which distinguishes these techniques into Block and Memory-Based FECs. Among the numerous techniques, four candidates have been detected and analyzed in Chapter 4. The candidates are 5G NR LDPC, 5G NR Polar, LTE TBCC, and LTE Turbo. These techniques show high reliability for short-packet communications. Moreover, they allow parallel decoding, which reduces the decoding latencies. .

Chapter 4 analyzes the candidates in terms of reliability and latency.

Reliability is analyzed via simulation provided via a BCM toolkit, whereas the latency is provided in required clock cycles for decoding. This metric has been deducted from the results of previous publications listed in Chapter 4. A secondary analysis for reliability is proposed, with the introduction of a WLAN PHY layer simulator for testing the techniques in industrial scenarios. Two industrial channel models are provided, Scenario 7 and CM8. The best candidates have been 5G NR Polar with SCL decoding, suggested for critical communications, whereas 5G NR LDPC with BP decoding for critical communications. Table 6.2 summarizes the results obtained for the candidates for reliability and latency. The reliability results are obtained via a BCM simulator in MATLAB. These simulations propose QPSK as modulation and AWGN as the channel model. In this case, 5G NR Polar outperforms the others in the configurations proposed for code rate and payload. Nevertheless, 5G NR LDPC provides a slightly worsened performance. For latency, the results represent the decoding latency, deducted by the literature review. In this case, 5G NR LPC promises the lowest latencies for the proposed payload and code rate configurations. Indeed, due to the full parallelism property, the number of clock cycles required for decoding the data block is reduced.

In addition, Chapter 2 introduces several innovative FEC techniques to improve the reliability and performance of wireless communication systems. Then, Chapter 3 addresses novel decoding algorithms to enhance the decoding efficiency of these FEC techniques. These contributions are described as follows.

6.2.2.1 New Decoding Algorithms for the FEC candidates

CA-Polar is a hot topic concerning the coding theory due to its demonstrated performance for short packet transmissions. Traditionally, SCL is the decoding algorithm adopted with this FEC. Nevertheless, novelties such as SCF and Sphere decoding algorithms could achieve SCL performance with lower latencies. Therefore further studies in this direction are needed. Finally, offers a detailed description of the proposal with a guideline for its hardware implementation. Nevertheless, this work lacks comparable results; consequently, preliminary studies must be conducted to evaluate the algorithm's performance with simulations,

Table 6.2: Comparison results of the FEC candidates

Candidate	Algorithm	Payload [B]	SNR [dB] BLER @ 10^{-6}, R =0.5	SNR [dB] BLER @ 10^{-6}, R =0.3	Decoding Latency [μs], R =0.5	Decoding Latency [μs], R =0.3
5G NR LDPC	BP	16	5.4	2.5	0.017	0.01
5G NR LDPC	BP	32	4	1.7	0.017	0.01
5G NR LDPC	BP	64	2.8	1.3	0.017	0.01
5G NR Polar	SCL	16	5	2.3	0.027	0.067
5G NR Polar	SCL	32	3.7	1.7	0.05	0.13
5G NR Polar	SCL	64	2.7		0.11	
LTE Turbo	Log MAP	16	6	3	0.053	0.053
LTE Turbo	Log MAP	32	4.7	2.3	0.053	0.053
LTE Turbo	Log MAP	64	3.5	1.3	0.053	0.053
LTE TBCC	WAVA	16	6.3	3.5	0.41	0.42
LTE TBCC	WAVA	32	6.3	3.5	0.43	0.44
LTE TBCC	WAVA	64	6.3	3.5	0.45	0.48

considering AWGN and industrial channel models.

6.2.2.2 Novelties on FEC techniques

SVC has recently emerged as a potential FEC technique for extremely short packet transmission (payloads below 100 bits), offering performance comparable to CA-Polar. Preliminary studies show that SVC has limitations in code rate values (lower or equal to 1/4) and modulations. Nevertheless, SVC could be considered an excellent candidate for future FA applications, particularly in safety communications. Therefore, its hardware implementation toward ultra-low latency communications is a future challenge.

PAC, recently introduced by Arikan, also presents capabilities as a future candidate for FA communications, potentially outperforming CA-Polar. Nevertheless, the studies presented are preliminary, showing a few contributions focused on decoding algorithms. PAC could potentially be a potential FA candidate if combined with decoding algorithms designed for low-latency communications. Therefore, developing decoding algorithms will be a hot topic and raise interest in future studies.

6.2.2.3 Towards the use of non-linear codes in FA applications

The binarization of the Preparata and Kerdock codes combined with low complex decoding algorithms addresses future challenges for low latency communications [39]. In this first proposal, only the MAP decoding algorithm has been considered. Therefore the following challenges have been detected. First, a hardware implementation must be conducted as it could open new frontiers for low latency communications and FA. Second, different decoding algorithms suitable for FA environments, such as BP or SCL, must be tested and compared with the results of adopting MAP, as this research topic shows only this preliminary contribution.

6.2.3 Analysis and proposals of a deterministic OFDMA technique for industrial wireless systems

In Chapters 2 and 5, after analyzing the deterministic MAC techniques for the Factory Automation use cases, another contribution is the description of an optimized IEEE 802.11ax for the most demanding use cases. The classification proposes three MAC families: TDMA, OFDMA and Multilink Operations. Among the use cases, the following scenario has been proposed: real-time communications among robots for the stocking process within warehouses. This use case require high-dense networks with high requirements for latency and reliability. In this study, 32 devices are assumed between AGV and AMR. OFDMA has been considered the MAC layer approach for its reliability, latency, and multi-user communications capabilities.

Chapter 5 contains the details of this proposal, which defines the network topology, the PHY layer optimized waveform, two MAC algorithms for exploiting the retransmissions on the frequency domain. Finally, the definition of the deterministic superframe and its messages is included.

These proposals are simulated and compared in terms of reliability and latency. For reliability the two methodologies are compared with a TDMA approach. The simulation evaluate the network reliability in the presence of the industrial channel models CM7 and CM8. Then, the latency is evaluated considering the superframe duration, compared with the results obtained with w-SHARP.

This system shows improved performance with respect to previous proposals, as highlighted in Tables 6.3 and 6.4. Table 6.3 shows the reliability performance assuming CM7 and CM8 as channel models. Both proposals outperform the TDMA approach. Among these, Methodology 2 is the best solution. For CM8, Methodology 2 is 7.5dB better than TDMA and 5.5 dB than Methodology 1. Finally, regarding CM7, these distances are reduced due to better channel conditions. In this case, the difference with TDMA is 3 dB and only 1 dB with Methodology 1.

Latency results are observable in Table 6.4. The optimized PHY layer proposal requires $40\ \mu s$ less than w-SHARP, taking into account MCS1, BW of 160 MHz, and a payload of 13 B.

Table 6.3: Reliability results for the MAC proposals

MAC technique	**SNR [dB] for CM7, BLER** @ 10^{-6}	**SNR [dB] for CM8, BLER** @ 10^{-6}
TDMA	12	16
Methodology 1	10	14
Methodology 2	9	9.5

Table 6.4: Superframe duration

Superframe	**Nº Users**	**Latency [** μs**]**
w-SHARP	32	180
Optimized IEEE 802.11ax	32	140

6.3 Dissemination

6.3.1 International Journal 1

- **Title:** "A Survey on FEC Techniques for Industrial Wireless Communications"
- **Authors:** Lorenzo Fanari, Eneko Iradier, Iñigo Bilbao, Rufino Cabrera, Jon Montalban, Pablo Angueira, Oscar Seijo, Iñaki Val
- **Publication:** IEEE Open Journal of the Industrial Electronics Society
- **Date of Publication:** 04 November 2022
- **Contribution:** This article surveys existing FEC techniques for short packet transmissions. Compared to other survey papers in the field, we propose several FEC candidate techniques specifically suitable for FA wireless systems.Four of these techniques are explored, also examining hardware architecture proposals. This article proposes a methodology to evaluate their latency and reliability performance. Finally,some discussions are carried out for the lessons learned and challenges for future research.

6.3.2 International Journal 2

- **Title:** "Comparison between Different Channel Coding Techniques for IEEE 802.11be within Factory Automation Scenarios"
- **Authors:** Lorenzo Fanari, Eneko Iradier, Iñigo Bilbao, Rufino Cabrera, Jon Montalban, Pablo Angueira
- **Publication:** MPDI Sensors
- **Date of Publication:** 29 October 2021
- **Contribution:** This paper presents improvements in the physical layer reliability of the IEEE 802.11be standard. Most wireless system proposals do not fulfill the stringent requirements of Factory Automation use cases. The harsh propagation features of industrial environments usually require time retransmission techniques to guarantee link reliability. At the same time, retransmissions compromise latency.

  IEEE 802.11be, the upcoming WLAN standard, is being considered for Factory Automation (FA) communications. 802.11be addresses specifically latency and reliability difficulties, typical in the previous 802.11 standards.

  This paper evaluates different channel coding techniques potentially applicable in IEEE 802.11be. The methods suggested here are the following: WLAN LDPC, WLAN Convolutional Codes (CC), New Radio (NR) Polar, and Long Term Evolution (LTE)-based Turbo Codes. The tests consider an IEEE 802.11be prototype under the Additive White Gaussian Noise (AWGN) channel and industrial channel models. The results suggest that the best performing codes in factory automation cases are the WLAN LDPCs and New Radio Polar Codes.

6.3.3 International Journal 3

- **Title:** "Optimized IEEE 802.11ax for Smart Warehouses"
- **Authors:** Lorenzo Fanari, Dreyelian Morejón, Iñigo Bilbao, Eneko Iradier, Jon Montalban, Pablo Angueira
- **Publication:** Elsevier Ad-Hoc Networks
- **Date of Publication:** TBA
- **Contribution:** This article proposes an ad-hoc wireless system based on IEEE 802.11ax for smart warehouses that comprises optimization for MAC and PHY layers. Furthermore, two retransmission schemes based on frequency domain are described. This article proposes a methodology to evaluate the latency and reliability performance. Compared to previous proposals, the system shows improved performance.

6.3.4 International Conference 1

- **Title:** PEG-LDPC Coding for Critical Communications in Factory Automation
- **Authors:** Lorenzo Fanari, Eneko Iradier, Jon Montalban, Pablo Angueira, Oscar Seijo, Iñaki Val
- **Conference:** 2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)
- **Date of Conference:** 08-11 September 2020
- **Conference Location:** Vienna, Austria
- **Contribution:** Critical communication requirements included in Factory Automation applications are complex to implement due to the difficulties encountered in guaranteeing high reliability and ultra-low latencies at the same time. In this work, a technical solution for the physical layer is proposed: the Quasi-Cyclic LDPC of the Progressive Edge Growth family (QC-PEGLDPC).

  This coding scheme is considered as a promising candidate due to two main factors: the good decoding performance for short packet transmissions and the low latency that can be obtained by using full parallel decoding architectures. The obtained results are compared with the 5G New Radio coding scheme, which includes LDPCs as part of the solution for Ultra Reliable Low Latency (URLLC) use cases.

  In these first results, QC-PEG-LDPC shows a performance improvement of 1 dB when compared with the 5G LDPC codes for a message length of 128 bits. Latency analysis indicate that QC-PEG-LDPC could allow decoding latencies of 0.13 μs providing that the full parallel decoding architecture is enabled.

6.3.5 International Conference 2

- **Title:** Channel Coding for the Control Plane in Broadcast Networks
- **Authors:** Lorenzo Fanari, Iñigo Bilbao, Rufino Cabrera, Eneko Iradier, Jon Montalban, Pablo Angueira
- **Conference:** 2022 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)
- **Date of Conference:** 5-17 June 2022
- **Conference Location:** Bilbao, Spain
- **Contribution:** This paper considers different channel coding techniques suitable for the control plane signals that will be required for some of the services enabled by the ATSC 3.0 Broadcast Core Network (BCN). Short packet and variable code rates are necessary for control plane communications.

  The suggested techniques are included in the 5G New Radio (NR) and IEEE 802.11 standards. LDPC and CRC-aided (CA) Polar for 5G NR, while Convolution Codes are the main solution for WLAN communications. On the one hand, the study comprises a discussion on the impact of the technical solutions into the core network architectural aspects. On the other hand, the reliability performance of the candidates is evaluated under the Additive White Gaussian Noise Channel (AWGN) for different code rates. The results show that 5G NR CA-Polar is the best candidate.

6.3.6 International Conference 3

- **Title:** LDPC Matrix Analysis for Short Packet Transmission in Factory Automation Scenarios

- Authors: Lorenzo Fanari, Eneko Iradier, Jon Montalban, Pablo Angueira, Oscar Seijo, Iñaki Val

- **Conference:** 2020 IEEE International Conference on Electrical Engineering and Photonics (EExPolytech)

- **Date of Conference:** 15-16 October 2020

- **Conference Location:** St. Petersburg, Russia

- **Contribution:** Critical application requirements proposed for Factory Automation scenarios involve demanding and simultaneous restrictions in reliability and latency. Channel coding is a basic tool to guarantee reliability but it usually involves high computation and memory resources at both transmitting and receiving sides.

  Among all the possible choices, Low Density Parity Check codes provide outstanding correction capacity. This paper studies two different LDPC coding approaches: 5G New Radio (5G NR) and IEEE 802.11 (WLAN). One of the drawbacks of LDPCs is their degraded performance and complex matrix adaptation for short information packets. Both 5G and 802.11 LDPCs use Quasi-Cyclic LDPC as the adaptation technique for matching the data packet size and coding matrix dimension.

  This paper evaluates 5G and 802.11 LDPC techniques, analyzing their structure and reliability performance for very short information messages by means of simulations. The results show that 5G NR LDPC is 1 dB closer to the Shannon limit than WLAN LDPCs, but this gain is lost for short message lengths as the ones used in Factory Automation environments. However, latency results are promising due to the opportunity of combining the analyzed techniques with new MAC techniques in order to achieve the desired reliability while not affecting latency dramatically.

6.4 Future Works

During the development of this Ph.D. thesis, future research lines have been identified to complement or extend each contribution of this work.

For the first contribution, the following future works have been detected.

- Industrial Channels Models: The literature provides a reduced number of industrial channel models. In addition, the majority of them are outdated. The more channel models are provided, the more accurate will be the analysis of the performance of the industrial wireless systems.
- Metrics for short packet communications: The need for metrics for short packet analysis emerged due to the interest in URLLC applications of this last decade. Many boundaries for evaluating the performance in generic fading channels have been proposed. Nevertheless, the actual proposals could not be helpful in industrial channels. Consequently, the proposal of boundaries associated with the industrial channel models could be highly relevant in the next future.

The second contribution offers the following future research.

- Hardware implementations of the FEC novelties: Several novelties, such as SVC, PAC, and non-linear codes, have recently been introduced for short packet communications. Their research is in the first steps, and the published results are encouraged. For this reason, it is interesting to provide their hardware implementation results in the immediate future. These techniques will help address the requirements for the more demanding use cases for Factory Automation.
- New decoding algorithms: Novelties like SCF and Sphere algorithms are promising and require further analysis: Two directions are detected. First, the study of their performance via simulations of industrial environments. Second, the proposal for hardware implementations. Their usage could reduce the latency performance of Polar codes, for example.

Finally, the following future works have been detected from the third contribution.

- High Performance stand-alone wireless system: The results provided in this thesis highlight that the combination of deterministic MAC layers, with FEC for the short packet at the PHY layer, could be the solution for highly critical scenarios, such as safety communications or for high-dense networks in critical communications.

- Build a hardware prototype of the optimized IEEE 802.11ax: The results proposed in Chapter 5 encourage future research related to its hardware development.

Glossary

This Section provides the list of abbreviations proposed in this thesis. They are alphabetically ordered.

List of Abbreviations

3GPP	3rd Generation Partnership Project
5G NR	5G New Radio
AP	Access Point
AR3A	Accumulate-Repeat-3-Accumulate
AR4JA	Accumulate-Repeat-by4-Jagged-Accumulate
AWGN	Additive White Gaussian Noise
ASIC	Application Specific Integrated Circuit
ASIP	Application-Specific Instruction Set Processor
ATSC	Advanced Television Systems Committee
ARQ	Automatic Repeat reQuest
BM	Base Matrix
BP	Belief Propagation
BPSK	Binary Phase-Shift Keying
B-DMC	Binary-Input Discrete Memoryless Channel
BCM	Bit Coded Modulation
BER	Bit Error Rate
BLER	Block Error Rate

BCH	Bose–Chaudhuri–Hocquenghem
BPM	Burst Position Modulation
CSMA	Carrier Sense Multiple Access with Collision Detection
CM	Channel Model
CVA	Circular Viterbi algorithm
CCSDS	Consultative Committee for Space Data Systems
CC	Convolutional Codes
CA-Polar	CRC-aided Polar
CRC	Cyclic Redundancy Check
DSSS	Direct Sequence Spread Spectrum
DVB-S2	Digital Video Broadcasting - Satellite - Second Generation
DVB-T2	Digital Video Broadcasting - Second Generation Terrestrial
DL	Downlink
E2E	End-to-End Latency
EHT	Extremely High Throughput
FA	Factory Automation
FPGA	Field Programmable Gate Arrays
FEC	Forward Error Correction
GPU	Graphics Processing Unit
HART	Highway Addressable Remote Transducer Protocol
HARQ	Hybrid Automatic Repeat reQuest
HAR2D-FI	Hybrid channel Access with Redundancy for Reliable and Deterministic Wi-Fi
IEC	International Electrotechnical Commission
ISM	Industrial Medical Scientific Band
ISA	Interantional Society of Automation
KPI	Key Performance Indicator
LoS	Line-of-Sight
LDPC	Low Density Parity Check
LLR	Logarithmic Likelihood Ratio

LTE	Long Term Evolution
LTF	Long Training field
LT	Luby Transform
MAP	Maximum-A-Posteriori
MediaFLO	Media Forward Link Only
MAC	Medium Access Control Layer
MBMS	Multimedia Broadcast Multicast Services
NASA	National Aeronautics and Space Administration
NLoS	Non Line-of-Sight
OMNET++	Objective Modular Network Testbed in C++
OSI	Open Systems Interconnection model
OSD	Ordered Statistics Decoding
OFDMA	Orthogonal Frequency Division Multiple Access
OFDM	Orthogonal Frequency Division Multiplexing
PER	Packet Error Rate
PLR	Packet Loss Rate
PCCC	Parallel Concatenated Convolutional Codes
H	Parity Check Matrix
PHY	Physical Layer
PPDU	Physical Layer Protocol Data Unit
PAC	Polarization-adjusted Convolutional codes
PEG	Power Edge Growth
PA	Process Automation
QPSK	Quadrature Phase-Shift Keying

QC	Quasi-Cyclic
RAN	Radio Access Network
RS	Reed-Solomon
RU	Resource Unit
rTx	re-Transmission
SCCC	Serial Concatenated Convolutional Codes
SRPT	Shortest Remaining Processing Time
STF	Short Training fields
SNR	Signal-to-Noise Ratio
SDR	Software-defined Radio
STA	Station
SVC	Sparse Vector Code
SCF	Successive Cancellation Flip
SCL	Successive Cancellation List
SHARP	Synchronous and Hybrid Architecture and for Real-time Performance
TBCC	Tailbiting Convolutional Codes
TDMA	Time Division Multiple Access
TPC	Turbo Product Codes
URLLC	Ultra-Reliable Low Latency Communications
UWB	Ultra-Wideband
UMTS	Universal Mobile Telecommunications System
USRP	Universal Software Radio Peripherals
UL	Uplink
WirelessHP	Wireless High-Performance
WIA-FA	Wireless networks for Industrial Automation -Factory Automation
WPAN	Wireless Personal Area Network
WiMAX	Worldwide Interoperability for Microwave Access
WAVA	Wrap-Around Viterbi algorithm
ZTBCC	Zero Tailbiting Convolutional Codes

Bibliography

[1] Martin Wollschlaeger, Thilo Sauter, and Juergen Jasperneite. The future of industrial communication: Automation networks in the era of the internet of things and industry 4.0. *IEEE Industrial Electronics Magazine*, 11(1):17–27. See pages 3, 54.

[2] Johan Akerberg, Mikael Gidlund, and Mats Björkman. Future research challenges in wireless sensor and actuator networks targeting industrial automation. In *2011 9th IEEE International Conference on Industrial Informatics*, pages 410–415, July 2011. See pages 3, 23.

[3] Richard Candell and Mohamed Kashef. Industrial wireless: Problem space, success considerations, technologies, and future direction. In *2017 Resilience Week (RWS)*, pages 133–139, Sep. 2017. See pages 3, 23, 24, and 55.

[4] Michele Luvisotto, Zhibo Pang, and Dacfey Dzung. High-performance wireless networks for industrial control applications: New targets and feasibility. *Proceedings of the IEEE*, 107(6):1074–1093, June 2019. See pages 3, 5, 23, 24, 25, 31, 33, 45, and 68.

[5] Dave Cavalcanti, Javier Perez-Ramirez, Mohammad Mamunur Rashid, Juan Fang, Mikhail Galeev, and Kevin B. Stanton. Extending accurate time distribution and timeliness capabilities over the air to enable future wireless industrial automation systems. *Proceedings of the IEEE*, 107(6):1132–1152, June 2019. See pages 3, 23, 24, 26, 55, and 56.

[6] Gordon J. Sutton, Jie Zeng, Ren Ping Liu, Wei Ni, Diep N. Nguyen,

Beeshanga A. Jayawickrama, Xiaojing Huang, Mehran Abolhasan, Zhang Zhang, Eryk Dutkiewicz, and Tiejun Lv. Enabling technologies for ultra-reliable and low latency communications: From phy and mac layer perspectives. *IEEE Communications Surveys Tutorials*, 21(3):2488–2524, thirdquarter 2019. See pages 3, 23, 24, and 26.

[7] Karl Montgomery, Richard Candell, Yongkang Liu, and Mohamed Hany. Wireless user requirements for the factory workcell, 2019-10-02 2019. See pages 3, 5, 21, 23, 24, 25, 27, 54, 55, 56, 58, 68, 117, and 133.

[8] Philipp Schulz, Maximilian Matthe, Henrik Klessig, Meryem Simsek, Gerhard Fettweis, Junaid Ansari, Shehzad Ali Ashraf, Bjoern Almeroth, Jens Voigt, Ines Riedel, Andre Puschmann, Andreas Mitschele-Thiel, Michael Muller, Thomas Elste, and Marcus Windisch. Latency critical iot applications in 5g: Perspective on the design of radio interface and network architecture. *IEEE Communications Magazine*, 55(2):70–78, February 2017. See pages 3, 23, 24, and 27.

[9] Lorenzo Fanari, Eneko Iradier, Iñigo Bilbao, Rufino Cabrera, Jon Montalban, Pablo Angueira, Oscar Seijo, and Iñaki Val. A survey on fec techniques for industrial wireless communications. *IEEE Open Journal of the Industrial Electronics Society*, 3:674–699, 2022. See pages 5, 6, 21, 45, 58, 66, 69, and 132.

[10] Pablo Angueira, Iñaki Val, Jon Montalban, OÓscar Seijo, Eneko Iradier, Pablo Sanz Fontaneda, Lorenzo Fanari, and Aitor Arriola. A survey of physical layer techniques for secure wireless communications in industry. *IEEE Communications Surveys & Tutorials*, 24(2):810–838, 2022. See pages 5, 21, 45, 66, and 132.

[11] Michele Luvisotto, Zhibo Pang, Dacfey Dzung, Ming Zhan, and Xiaolin Jiang. Physical layer design of high-performance wireless transmission for critical control applications. *IEEE Transactions on Industrial Informatics*, 13(6):2844–2854, Dec 2017. See pages 5, 31, 33, 58, 66, 67, 93, and 122.

[12] Jon Montalban, Eneko Iradier, Pablo Angueira, Oscar Seijo, and Iñaki Val. Noma-based 802.11n for industrial automation. *IEEE Access*, 8:168546–168557, 2020. See pages 5, 45, 66, 67, 82, 96, 113, 118, and 119.

[13] Eneko Iradier, Lorenzo Fanari, Iñigo Bilbao, Jon Montalban, Pablo Angueira, Oscar Seijo, and Iñaki Val. Analysis of noma-based retrans-

mission schemes for factory automation applications. *IEEE Access*, 9:29541–29554, 2021. See pages 5, 66, 67, 96, 101, 113, and 118.

[14] Ramona Croonenbroeck, Lisa Underberg, Armin Wulf, and Rüdiger Kays. Measurements for the development of an enhanced model for wireless channels in industrial environments. In *2017 IEEE 13th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, pages 1–8, 2017. See pages 5, 45, 75, 95, 116, 118, and 119.

[15] David Lopez-Perez, Adrian Garcia-Rodriguez, Lorenzo Galati-Giordano, Mika Kasslin, and Klaus Doppler. Ieee 802.11be extremely high throughput: The next generation of wi-fi technology beyond 802.11ax. *IEEE Communications Magazine*, 57(9):113–119, Sep. 2019. See pages 6, 30, 46, and 48.

[16] Cailian Deng, Xuming Fang, Xiao Han, Xianbin Wang, Li Yan, Rong He, Yan Long, and Yuchen Guo. Ieee 802.11be-wi-fi 7: New challenges and opportunities, 2020. See pages 6, 29, 33, 58, 97, 100, 120, 123, 124, and 133.

[17] Oscar Seijo, Jesús Alberto López-Fernández, and Iñaki Val. w-sharp: Implementation of a high-performance wireless time-sensitive network for low latency and ultra-low cycle time industrial applications. *IEEE Transactions on Industrial Informatics*, 17(5):3651–3662, May 2021. See pages 6, 30, 33, 46, 48, 49, 93, 132, and 133.

[18] L. Fanari, E. Iradier, J. Montalban, P. Angueira, Oscar Seijo, and Iñaki Val. Peg-ldpc coding for critical communications in factory automation. In *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, volume 1, pages 1135–1138, Sep. 2020. See pages 21, 44, 70, and 89.

[19] Javier Perez-Ramirez, Oscar Seijo, and Iñaki Val. Time-critical iot applications enabled by wi-fi 6 and beyond. *IEEE Internet of Things Magazine*, 5(3):44–49, 2022. See pages 22, 46, and 49.

[20] Evgeny Khorov, Anton Kiryanov, Andrey Lyakhov, and Giuseppe Bianchi. A tutorial on ieee 802.11ax high efficiency wlans. *IEEE Communications Surveys Tutorials*, 21(1):197–216, Firstquarter 2019. See pages 30, 33.

[21] Robson Costa, Jim Lau, Paulo Portugal, Francisco Vasques, and Ricardo Moraes. Handling real-time communication in infrastructured ieee 802.11 wireless networks: The rt-wifi approach. *Journal of Com-*

munications and Networks, 21(3):319–334, June 2019. See pages 30, 46, and 48.

[22] Aneeq Mahmood, Thilo Sauter, Henning Trsek, and Reinhard Exel. Methods and performance aspects for wireless clock synchronization in ieee 802.11 for the iot. In *2016 IEEE World Conference on Factory Communication Systems (WFCS)*, pages 1–4, May 2016. See page 30.

[23] Wei Shen, Tingting Zhang, Filip Barac, and Mikael Gidlund. Priority-mac: A priority-enhanced mac protocol for critical traffic in industrial wireless sensor and actuator networks. *IEEE Transactions on Industrial Informatics*, 10(1):824–835, Feb 2014. See page 30.

[24] Adnan Aijaz. High-performance industrial wireless: Achieving reliable and deterministic connectivity over ieee 802.11 wlans. *IEEE Open Journal of the Industrial Electronics Society*, 1:28–37, 2020. See pages 30, 46, and 49.

[25] Oscar Seijo, Zaloa Fernández, Iñaki Val, and Jesús A. López-Fernández. Sharp: Towards the integration of time-sensitive communications in legacy lan/wlan. In *2018 IEEE Globecom Workshops (GC Wkshps)*, pages 1–7, Dec 2018. See pages 30, 33, 46, 47, and 58.

[26] Oscar Seijo, Zaloa Fernández, Iñaki Val, and Jesús A. López-Fernández. Sharp: A novel hybrid architecture for industrial wireless sensor and actuator networks. In *2018 14th IEEE International Workshop on Factory Communication Systems (WFCS)*, pages 1–10, June 2018. See pages 30, 33, 43, 46, 47, 67, 68, and 124.

[27] Ieee standard for information technology– local and metropolitan area networks– specific requirements– part 15.4: Wireless medium access control (mac) and physical layer (phy) specifications for low rate wireless personal area networks (wpans). *IEEE Std 802.15.4-2006 (Revision of IEEE Std 802.15.4-2003)*, pages 1–320, Sep. 2006. See pages 30, 33.

[28] P. Losco, S. Bourdel, J. Gaubert, N. Dehaese, S. Meillère, O. Ramos, R. Vauche, and H. Barthelemy. Analysis of the ieee 802.15.4a uwb phy layer for optimizing the power consumption of the transmitter. In *2013 IEEE International Conference on Ultra-Wideband (ICUWB)*, pages 189–194, Sep. 2013. See page 30.

[29] Ville Niemelä, Jussi Haapola, Matti Hämäläinen, and Jari Iinatti. An ultra wideband survey: Global regulations and impulse radio re-

search based on standards. *IEEE Communications Surveys Tutorials*, 19(2):874–890, Secondquarter 2017. See page 30.

[30] Eirini Karapistoli, Fotini-Niovi Pavlidou, Ioannis Gragopoulos, and Ioannis Tsetsinas. An overview of the ieee 802.15.4a standard. *IEEE Communications Magazine*, 48(1):47–53, January 2010. See page 31.

[31] Ieee standard for low-rate wireless networks–amendment 1: Enhanced ultra wideband (uwb) physical layers (phys) and associated ranging techniques. *IEEE Std 802.15.4z-2020 (Amendment to IEEE Std 802.15.4-2020)*, pages 1–174, Aug 2020. See pages 31, 33.

[32] 3GPP. Digital cellular telecommunications system (Phase 2+) (GSM); Universal Mobile Telecommunications System (UMTS); LTE; 5G;. Technical Report (TR) 121 915, 3rd Generation Partnership Project (3GPP), 10 2019. Version 15.0.0. See pages 31, 33, and 35.

[33] Muhammad A. Imran, Sajjad Hussain, and Qammer H. Abbasi. *Industrial Wireless Sensor Networks Overview*, pages 1–17. IEEE, 2020. See pages 31, 33.

[34] Zhibo Pang, Michele Luvisotto, and Dacfey Dzung. Wireless high-performance communications: The challenges and opportunities of a new target. *IEEE Industrial Electronics Magazine*, 11(3):20–25, Sep. 2017. See pages 31, 33, and 58.

[35] M. Zhan, Z. Pang, D. Dzung, M. Luvisotto, K. Yu, and M. Xiao. Towards high-performance wireless control: -7$ packet error rate in real factory environments. *IEEE Transactions on Industrial Informatics*, 16(8):5554–5564. See pages 32, 58.

[36] M. Zhan, Z. Pang, D. Dzung, and M. Xiao. Channel coding for high performance wireless control in critical applications: Survey and analysis. *IEEE Access*, 6:29648–29664, 2018. See pages 33, 35, 36, 40, 41, 63, 64, 66, 67, 68, 82, and 89.

[37] Joachim Sachs, Gustav Wikstrom, Torsten Dudda, Robert Baldemair, and Kittipong Kittichokechai. 5g radio network design for ultra-reliable low-latency communication. *IEEE Network*, 32(2):24–31, March 2018. See pages 33, 46, and 47.

[38] Xiaolin Jiang, Michele Luvisotto, Zhibo Pang, and Carlo Fischione. Latency performance of 5g new radio for critical industrial control systems. In *2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, pages 1135–1142, Sep. 2019. See page 33.

[39] Aleksandar Minja and Vojin Senk. Siso decoding of z4 linear kerdock and preparata codes. *IEEE Transactions on Communications*, 70(3):1497–1507, 2022. See pages 35, 37, and 144.

[40] R. Gallager. Low-density parity-check codes. *IRE Transactions on Information Theory*, 8(1):21–28. See pages 35, 38.

[41] M. C. Davey and D. MacKay. Low-density parity check codes over GF(q). *IEEE Communications Letters*, 2(6):165–167. See page 35.

[42] Iso/iec/ieee international standard - information technology–telecommunications and information exchange between systems local and metropolitan area networks–specific requirements part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications. *ISO/IEC/IEEE 8802-11:2012(E) (Revison of ISO/IEC/IEEE 8802-11-2005 and Amendments)*, pages 1–2798, Nov 2012. See pages 35, 37.

[43] Koon Hoo Teo, Zhifeng Tao, and Jinyun Zhang. The mobile broadband wimax standard [standards in a nutshell]. *IEEE Signal Processing Magazine*, 24(5):144–148, Sep. 2007. See pages 35, 40.

[44] Kyung-Joong Kim, Seho Myung, Sung-Ik Park, Jae-Young Lee, Makiko Kan, Yuji Shinohara, Jong-Woong Shin, and Jinwoo Kim. Low-density parity-check codes for atsc 3.0. *IEEE Transactions on Broadcasting*, 62(1):189–196, March 2016. See page 35.

[45] Jan R. Westra, Jan Mulder, Yi Ke, Davide Vecchi, Xiaodong Liu, Erol Arslan, Jiansong Wan, Qiongna Zhang, Sijia Wang, Frank van der Goes, and Klaas Bult. Design considerations for low-power analog front ends in full-duplex 10gbase-t transceivers. In *Proceedings of the IEEE 2014 Custom Integrated Circuits Conference*, pages 1–8, Sep. 2014. See page 35.

[46] Christopher J. Hansen. Wigig: Multi-gigabit wireless communications in the 60 ghz band. *IEEE Wireless Communications*, 18(6):6–7, December 2011. See page 35.

[47] Iñaki Eizmendi, Manuel Velez, David Gómez-Barquero, Javier Morgade, Vicente Baena-Lecuyer, Mariem Slimani, and Jan Zoellner. Dvb-t2: The second generation of terrestrial digital video broadcasting system. *IEEE Transactions on Broadcasting*, 60(2):258–271, June 2014. See page 35.

[48] Lorenzo Vangelista, Nevio Benvenuto, Stefano Tomasin, Chris Nokes, Jonathan Stott, Alessio Filippi, Marnix Vlot, Vittoria Mignone, and

Alberto Morello. Key technologies for next-generation terrestrial digital television standard dvb-t2. *IEEE Communications Magazine*, 47(10):146–153, October 2009. See page 35.

[49] A. Morello and V. Mignone. Dvb-s2: The second generation standard for satellite broad-band services. *Proceedings of the IEEE*, 94(1):210–227, Jan 2006. See page 35.

[50] Dimitris Theodoropoulos, Nektarios Kranitis, Antonis Tsigkanos, and Antonios Paschalis. Efficient architectures for multigigabit ccsds ldpc encoders. *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, 28(5):1118–1127, May 2020. See page 35.

[51] M.P.C. Fossorier. Quasicyclic low-density parity-check codes from circulant permutation matrices. *IEEE Transactions on Information Theory*, 50(8):1788–1793. See pages 35, 38, 77, and 78.

[52] Kwang Soon Kim, Sang-Han Lee, Yun Hee Kim, and J.Y. Ahn. Design of binary ldpc code using cyclic shift matrices. *Electronics Letters*, 40:325 – 326, 04 2004. See pages 35, 38.

[53] Satoshi GOUNAI and Tomoaki Ohtsuki. Lowering error floor of irregular ldpc codes by crc and osd algorithm. *IEICE Transactions on Communications*, E89B, 01 2006. See pages 35, 78.

[54] M. Baldi, N. Maturo, G. Ricciutelli, and F. Chiaraluce. On the error detection capability of combined ldpc and crc codes for space telecommand transmissions. In *2016 IEEE Symposium on Computers and Communication (ISCC)*, pages 1058–1065, June 2016. See pages 35, 78.

[55] Ieee standard for information technology– local and metropolitan area networks– specific requirements– part 15.1a: Wireless medium access control (mac) and physical layer (phy) specifications for wireless personal area networks (wpan). *IEEE Std 802.15.1-2005 (Revision of IEEE Std 802.15.1-2002)*, pages 1–700, June 2005. See page 35.

[56] Mario Poggioni, Luca Rugini, and Paolo Banelli. Dvb-t/h and t-dmb: Physical layer performance comparison in fast mobile channels. *IEEE Transactions on Broadcasting*, 55(4):719–730, Dec 2009. See pages 35, 37.

[57] Ieee standard for information technology–telecommunications and information exchange between systems–local and metropolitan area networks–specific requirements-part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications amendment 3:

Enhancements for very high throughput in the 60 ghz band. *IEEE Std 802.11ad-2012 (Amendment to IEEE Std 802.11-2012, as amended by IEEE Std 802.11ae-2012 and IEEE Std 802.11aa-2012)*, pages 1–628, Dec 2012. See page 35.

[58] S. Arunkumar and T. Kalaivani. Fpga implementation of ccsds bch (63, 56) for satellite communication. In *2012 IEEE International Conference on Electronics Design, Systems and Applications (ICEDSA)*, pages 248–253, Nov 2012. See page 35.

[59] Greenhill Book. Tm synchronization and channel coding — summary of concept and rationale. 2006. See pages 35, 37.

[60] Murali R. Chari, Fuyun Ling, Ashok Mantravadi, Raghuraman Krishnamoorthi, Rajiv Vijayan, G. Kent Walker, and Rob Chandhok. Flo physical layer: An overview. *IEEE Transactions on Broadcasting*, 53(1):145–160, March 2007. See pages 35, 40.

[61] R. W. Hamming. Error detecting and error correcting codes. *The Bell System Technical Journal*, 29(2):147–160, April 1950. See pages 35, 38.

[62] M. J. E. Golay. The logic of bidirectional binary counters. *IRE Transactions on Electronic Computers*, EC-6(1):1–4. See pages 35, 38.

[63] A Hocquenghem. Codes correcteurs d'erreurs. *Chiffers*, 2:147–156. See pages 35, 38.

[64] R. C. Bose and D. K. Ray-Chaudhuri. On a class of error correcting binary group codes. *Information and Control*, 3(1):68–79. See pages 35, 38.

[65] R. C. Bose and D. K. Ray-Chaudhuri. Further results on error correcting binary group codes. *Information and Control*, 3(3):279–290. See pages 35, 38.

[66] D. E. Muller. Application of boolean algebra to switching circuit design and to error detection. *Transactions of the I.R.E. Professional Group on Electronic Computers*, EC-3(3):6–12. See pages 35, 38.

[67] I. S. Reed and G. Solomon. Polynomial codes over certain finite fields. *Journal of the Society for Industrial and Applied Mathematics*, 8(2):300–304. Publisher: Society for Industrial and Applied Mathematics. See pages 36, 38.

[68] E. M. Gabidulin. Theory of codes with maximum rank distance. Problems Inform. Transmission, 21:1:1–12. See pages 36, 38.

[69] E. Arikan. A performance comparison of polar codes and reed-muller codes. *IEEE Communications Letters*, 12(6):447–449, June 2008. See pages 36, 38.

[70] I. Tal and A. Vardy. List decoding of polar codes. *IEEE Transactions on Information Theory*, 61(5):2213–2226. See pages 36, 77, and 79.

[71] K. Niu and K. Chen. CRC-aided decoding of polar codes. *IEEE Communications Letters*, 16(10):1668–1671. See pages 36, 77, and 79.

[72] A. Balatsoukas-Stimming, M. B. Parizi, and A. Burg. LLR-based successive cancellation list decoding of polar codes. *IEEE Transactions on Signal Processing*, 63(19):5165–5179. See pages 36, 77, and 79.

[73] O. Park, G. Y. Park, and Y. H. Lee. Improvement of ordered statistics decoding for low-rate bch codes. In *2019 International Conference on Information and Communication Technology Convergence (ICTC)*, pages 837–839, Oct 2019. See page 36.

[74] John W. Byers, Michael Luby, Michael Mitzenmacher, and Ashutosh Rege. A digital fountain approach to reliable distribution of bulk data. In *Proceedings of the ACM SIGCOMM '98 Conference on Applications, Technologies, Architectures, and Protocols for Computer Communication*, SIGCOMM '98, page 56–67, New York, NY, USA, 1998. Association for Computing Machinery. See page 36.

[75] Davis William Ryan, Shu Lin. *Channel codes classical and modern*. Communications, information theory and signal processing. Cambridge University Press. See pages 36, 78.

[76] Liang He, Ke Lai, Jing Lei, and Ying Huang. A fast encoding of 3gpp mbms raptor codes based on operation instruction. *IEEE Communications Letters*, 24(1):3–6, Jan 2020. See page 36.

[77] Luke Fay, Lachlan Michael, David Gómez-Barquero, Nejib Ammar, and M. Winston Caldwell. An overview of the atsc 3.0 physical layer specification. *IEEE Transactions on Broadcasting*, 62(1):159–171, March 2016. See page 36.

[78] M. Luby. LT codes. In *The 43rd Annual IEEE Symposium on Foundations of Computer Science, 2002. Proceedings.*, pages 271–280. ISSN: 0272-5428. See pages 36, 38.

[79] A. Kharel and L. Cao. Analysis and design of physical layer raptor codes. *IEEE Communications Letters*, 22(3):450–453, March 2018. See pages 36, 39.

[80] Michael Luby, Michael Mitzenmacher, and Ashutosh Rege. A digital fountain approach to reliable distribution of bulk data. page 15. See pages 36, 39.

[81] M. G. Luby, M. Mitzenmacher, M. A. Shokrollahi, and D. A. Spielman. Efficient erasure correcting codes. *IEEE Transactions on Information Theory*, 47(2):569–584. See pages 36, 39.

[82] Y. Ma, D. Yuan, and H. Zhang. Fountain codes and applications to reliable wireless broadcast system. In *2006 IEEE Information Theory Workshop - ITW '06 Chengdu*, pages 66–70, Oct 2006. See page 36.

[83] K. Zhang, J. Jiao, Z. Huang, S. Wu, and Q. Zhang. Finite block-length analog fountain codes for ultra-reliable low latency communications. *IEEE Transactions on Communications*, 68(3):1391–1404, 2020. See page 36.

[84] R. Abbas, M. Shirvanimoghaddam, T. Huang, Y. Li, and B. Vucetic. Novel design for short analog fountain codes. *IEEE Communications Letters*, 23(8):1306–1309, Aug 2019. See page 36.

[85] E. J. Candes and M. B. Wakin. An introduction to compressive sampling. *IEEE Signal Processing Magazine*, 25(2):21–30, March 2008. See page 36.

[86] H. Ji, S. Kim, and B. Shim. Sparse vector coding for ultra short packet transmission. In *2018 Information Theory and Applications Workshop (ITA)*, pages 1–9. See pages 36, 37, and 39.

[87] H. Ji, S. Park, and B. Shim. Sparse vector coding for 5g ultra-reliable and low latency communications. In *2018 IEEE International Conference on Communications (ICC)*, pages 1–6. ISSN: 1938-1883. See pages 36, 39.

[88] H. Ji and B. Shim. Sparse vector coding for short packet transmission in massive machine type communications. In *2018 24th Asia-Pacific Conference on Communications (APCC)*, pages 137–140. ISSN: 2163-0771. See pages 36, 39.

[89] R. Zhang, B. Shim, Y. Lou, S. Jia, and W. Wu. Sparse vector coding aided ultra-reliable and low-latency communications in multi-user massive MIMO systems. *IEEE Transactions on Vehicular Technology*, pages 1–1. See pages 37, 39.

[90] W. Kim, S. K. Bandari, and B. Shim. Enhanced sparse vector coding for ultra-reliable and low latency communications. *IEEE Transactions on Vehicular Technology*, 69(5):5698–5702, May 2020. See pages 37, 39.

[91] Fanxuan Zeng. *Nonlinear codes: representation, constructions, minimum distance computation and decoding*. Accepted: 2014-11-27T15:47:56Z ISBN: 9788449046216 Publication Title: TDX (Tesis Doctorals en Xarxa). See page 37.

[92] Franco P. Preparata. A class of optimum nonlinear double-error-correcting codes. *Information and Control*, 13(4):378–400. See pages 37, 39.

[93] A. M. Kerdock. A class of low-rate nonlinear binary codes. *Information and Control*, 20(2):182–187. See pages 37, 39.

[94] P Delsarte and J.M Goethals. Alternating bilinear forms over GF(q). *Journal of Combinatorial Theory, Series A*, 19(1):26–50. See pages 37, 39.

[95] P. Elias. Coding for noisy channels. *IRE Conv. Rec.*, 3, pt. 4:37–46, 1955. See pages 37, 42.

[96] Andreas Springer and Robert Weigel. *UMTS: The Physical Layer of the Universal Mobile Telecommunications System*. 01 2002. See page 37.

[97] H. Mousavi, Iraj S. Amiri, M.A. Mostafavi, and C.Y. Choon. Lte physical layer: Performance analysis and evaluation. *Applied Computing and Informatics*, 15(1):34–44, 2019. See pages 37, 40.

[98] D. Johnston, J.E. Graf, R.W. Zurek, H.J. Eisen, and B. Jai. The mars reconnaissance orbiter mission. In *2003 IEEE Aerospace Conference Proceedings (Cat. No.03TH8652)*, volume 1, pages 1–204 vol.1, March 2003. See page 40.

[99] H. Ma and J. Wolf. On tail biting convolutional codes. *IEEE Transactions on Communications*, 34(2):104–111. See pages 40, 42.

[100] A. Z. Ramdani and T. Adiono. A novel algorithm of tail biting convolutional code decoder for low cost hardware implementation. In *2015 International Symposium on Intelligent Signal Processing and Communication Systems (ISPACS)*, pages 241–245, Nov 2015. See pages 40, 42, 77, and 80.

[101] C. Berrou, A. Glavieux, and P. Thitimajshima. Near shannon limit error-correcting coding and decoding: Turbo-codes. 1. In *Proceedings of ICC '93 - IEEE International Conference on Communications*, volume 2, pages 1064–1070 vol.2. See pages 40, 42, and 80.

[102] C. Berrou and A. Glavieux. Near optimum error correcting coding and decoding: turbo-codes. *IEEE Transactions on Communications*, 44(10):1261–1271. See pages 40, 42.

[103] H. Mukhtar, A. Al-Dweik, and A. Shami. Turbo product codes: Applications, challenges, and future directions. *IEEE Communications Surveys Tutorials*, 18(4):3052–3069. See pages 40, 42.

[104] S. Benedetto, D. Divsalar, G. Montorsi, and F. Pollara. Serial concatenation of interleaved codes: performance analysis, design, and iterative decoding. *IEEE Transactions on Information Theory*, 44(3):909–926. See page 40.

[105] T. Abe, G. Bauch, and C. Hausl. A comparison of rate compatible PCCC and SCCC for next generation wireless communication systems. In *2006 3rd International Symposium on Wireless Communication Systems*, pages 766–770. ISSN: 2154-0225. See page 40.

[106] Z. Li, M. Miao, and Z. Wang. Parallel coding scheme with turbo product code for mobile multimedia transmission in mimo-fbmc system. *IEEE Access*, 8:3772–3780, 2020. See page 40.

[107] Yang Sun and Joseph R. Cavallaro. Efficient hardware implementation of a highly-parallel 3gpp LTE/LTE-advance turbo decoder. *Integration*, 44(4):305–315. See page 41.

[108] R. Shrestha and A. Sharma. Vlsi-architecture of radix-2/4/8 siso decoder for turbo decoding at multiple data-rates. In *2018 IFIP/IEEE International Conference on Very Large Scale Integration (VLSI-SoC)*, pages 131–136, Oct 2018. See page 41.

[109] Lukasz Lopacinski, Marcin Brzozowski, Joerg Nolte, Rolf Kraemer, and Steffen Buechner. Parallel rs error correction structures dedicated for 100 gbps wireless data link layer. In *2015 IEEE International Conference on Ubiquitous Wireless Broadband (ICUWB)*, pages 1–6, 2015. See page 41.

[110] Christoph Rachinger, Johannes B. Huber, and Ralf R. Müller. Comparison of convolutional and block codes for low structural delay. *IEEE Transactions on Communications*, 63(12):4629–4638, 2015. See page 41.

[111] Ming Zhan, Zhibo Pang, Ming Xiao, Michele Luvisotto, and Dacfey Dzung. Wireless high-performance communications: Improving effectiveness and creating ultrahigh reliability with channel coding. *IEEE Industrial Electronics Magazine*, 12(3):32–37, 2018. See pages 41, 61.

[112] Ieee standard for information technology–telecommunications and information exchange between systems local and metropolitan area networks–specific requirements part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications. *IEEE Std 802.11-2012 (Revision of IEEE Std 802.11-2007)*, pages 1–2793, 2012. See page 43.

[113] Dennis Hui, Sara Sandberg, Yufei Blankenship, Mattias Andersson, and Leefke Grosjean. Channel coding in 5g new radio: A tutorial overview and performance comparison with 4g lte. *IEEE Vehicular Technology Magazine*, 13(4):60–69, 2018. See pages 43, 44.

[114] Lorenzo Fanari, Eneko Iradier, Iñigo Bilbao, Rufino Cabrera, Jon Montalban, and Pablo Angueira. Comparison between different channel coding techniques for ieee 802.11be within factory automation scenarios. *Sensors*, 21(21), 2021. See pages 43, 67, 70, and 89.

[115] Shuai Shao, Peter Hailes, Tsang-Yi Wang, Jwo-Yuh Wu, Robert G. Maunder, Bashir M. Al-Hashimi, and Lajos Hanzo. Survey of turbo, LDPC, and polar decoder ASIC implementations. *IEEE Communications Surveys Tutorials*, 21(3):2309–2333. See pages 43, 63, 65, 68, and 83.

[116] Dmitry Bankov, Andre Didenko, Evgeny Khorov, and Andrey Lyakhov. Ofdma uplink scheduling in ieee 802.11ax networks. In *2018 IEEE International Conference on Communications (ICC)*, pages 1–6, 2018. See pages 46, 48.

[117] David González Filoso, Ryogo Kubo, Kazutaka Hara, Shinya Tamaki, Katsuya Minami, and Kohji Tsuji. Proportional-based resource allocation control with qos adaptation for ieee 802.11ax. In *ICC 2020 - 2020 IEEE International Conference on Communications (ICC)*, pages 1–6, 2020. See pages 46, 49.

[118] Sergei Tutelian, Dmitry Bankov, Dmitri Shmelkin, and Evgeny Khorov. Ieee 802.11ax ofdma resource allocation with frequency-selective fading. *Sensors*, 21(18), 2021. See pages 46, 49.

[119] Steven Dietrich, Gunther May, Oliver Wetter, Holger Heeren, and Gerhard Fohler. Performance indicators and use case analysis for wireless networks in factory automation. In *2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, pages 1–8, Sep. 2017. See pages 56, 61.

[120] Heinz Gall. Functional safety iec 61508 / iec 61511 the impact to certification and the user. In *2008 IEEE/ACS International Conference on Computer Systems and Applications*, pages 1027–1031, 2008. See pages 58, 67.

[121] Oscar Seijo, Zaloa Fernandez, Iñaki Val, and Jesus A. Lopez-Fernandez. Sharp: A novel hybrid architecture for industrial wireless sensor and actuator networks. In *2018 14th IEEE International Workshop on Factory Communication Systems (WFCS)*, pages 1–10, 2018. See pages 58, 119.

[122] Oscar Seijo, Jesus Alberto Lopez-Fernandez, and Iñaki Val. w-sharp: Implementation of a high-performance wireless time-sensitive network for low latency and ultra-low cycle time industrial applications. *IEEE Transactions on Industrial Informatics*, 17(5):3651–3662, 2021. See pages 58, 66, 113, 119, and 122.

[123] Federico Tramarin, Stefano Vitturi, Michele Luvisotto, and Andrea Zanella. On the use of ieee 802.11n for industrial communications. *IEEE Transactions on Industrial Informatics*, 12(5):1877–1886, 2016. See page 61.

[124] C. E. Shannon. A mathematical theory of communication. *The Bell System Technical Journal*, 27(3):379–423, 1948. See page 62.

[125] Giuseppe Durisi, Tobias Koch, and Petar Popovski. Towards massive, ultra-reliable, and low-latency wireless communication with short packets, 2016. See page 62.

[126] Yury Polyanskiy, H. Vincent Poor, and Sergio Verdu. Channel coding rate in the finite blocklength regime. *IEEE Transactions on Information Theory*, 56(5):2307–2359, 2010. See page 62.

[127] Michal Sybis, Krzysztof Wesolowski, Keeth Jayasinghe, Venkatkumar Venkatasubramanian, and Vladimir Vukadinovic. Channel coding for ultra-reliable low-latency communication in 5g systems. In *2016 IEEE 84th Vehicular Technology Conference (VTC-Fall)*, pages 1–5. See pages 63, 64, and 78.

[128] Gianluigi Liva, Lorenzo Gaudio, Tudor Ninacs, and Thomas Jerkovits. Code design for short blocks: A survey. *arXiv:1610.00873 [cs, math]*. See pages 63, 64, and 83.

[129] Onurcan Iscan, Diego Lentner, and Wen Xu. A comparison of channel coding schemes for 5g short message transmission. In *2016 IEEE Globecom Workshops (GC Wkshps)*, pages 1–6. See pages 63, 64.

[130] Zhenzhi Wu, Chen Gong, and Dake Liu. Computational complexity analysis of FEC decoding on SDR platforms. *J Sign Process Syst*, 89(2):209–224. See page 63.

[131] G. Tzimpragos, C. Kachris, I. B. Djordjevic, M. Cvijetic, D. Soudris, and I. Tomkos. A survey on FEC codes for 100 g and beyond optical networks. *IEEE Communications Surveys Tutorials*, 18(1):209–221. See pages 63, 64.

[132] Mahyar Shirvanimoghaddam, Mohammad Sadegh Mohammadi, Rana Abbas, Aleksandar Minja, Chentao Yue, Balazs Matuz, Guojun Han, Zihuai Lin, Wanchun Liu, Yonghui Li, Sarah Johnson, and Branka Vucetic. Short block-length codes for ultra-reliable low latency communications. *IEEE Communications Magazine*, 57(2):130–137. See pages 63, 64, and 96.

[133] W. Qiao, D. Liu, and S. Liu. QFEC ASIP: A flexible quad-mode FEC ASIP for polar, LDPC, turbo, and convolutional code decoding. *IEEE Access*, 6:72189–72200. See pages 63, 64.

[134] Zahraa Raad Mayoof Hajiyat, Aduwati Sali, Makhfudzah Mokhtar, and Fazirulhisyam Hashim. Channel coding scheme for 5g mobile communication system for short length message transmission. *Wireless Pers Commun*, 106(2):377–400. Number: 2. See pages 63, 65.

[135] Ashfaq Ahmed, Arafat Al-Dweik, Youssef Iraqi, Husameldin Mukhtar, Muhammad Naeem, and Ekram Hossain. Hybrid automatic repeat request (harq) in wireless communications systems and standards: A contemporary survey. *IEEE Communications Surveys Tutorials*, 23(4):2711–2752, 2021. See pages 63, 65.

[136] Salman Habib, Allison Beemer, and Jörg Kliewer. Belief propagation decoding of short graph-based channel codes via reinforcement learning. *IEEE Journal on Selected Areas in Information Theory*, 2(2):627–640, 2021. See pages 63, 65.

[137] Bo Lian and Frank R. Kschischang. Sequential decoding of short length binary codes: Performance versus complexity. *IEEE Communications Letters*, 25(10):3195–3198, 2021. See pages 63, 65.

[138] Oscar Ferraz, Srinivasan Subramaniyan, Ramesh Chinthalaa, João Andrade, Joseph R. Cavallaro, Soumitra K. Nandy, Vitor Silva, Xinmiao Zhang, Madhura Purnaprajna, and Gabriel Falcao. A survey on high-throughput non-binary ldpc decoders: Asic, fpga, and gpu architectures. *IEEE Communications Surveys & Tutorials*, 24(1):524–556, 2022. See pages 63, 65, and 68.

[139] D. Wu, Y. Li, X. Guo, and Y. Sun. Ordered statistic decoding for short polar codes. *IEEE Communications Letters*, 20(6):1064–1067. See pages 64, 85, and 86.

[140] Samsung. Discussion on latency of channel codes for NR. 3GPP TSG RAN WG1 86bis R1-1609073. See pages 70, 89, and 93.

[141] Andreas F. Molisch, Kannan Balakrishnan, Dajana Cassioli, Chia-Chin Chong, Shahriar Emami, Andrew Fort, Johan, Karedal, Juergen Kunisch, Hans Gregory Schantz, Ulrich G. Schuster, and Kai Siwiak. Ieee 802.15.4a channel model-final report. 2004. See pages 75, 95, 116, and 118.

[142] Xiao-Yu Hu, E. Eleftheriou, and D. M. Arnold. Regular and irregular progressive edge-growth tanner graphs. *IEEE Transactions on Information Theory*, 51(1):386–398. See pages 77, 78.

[143] E. Arikan. Channel polarization: A method for constructing capacity-achieving codes for symmetric binary-input memoryless channels. *IEEE Transactions on Information Theory*, 55(7):3051–3073. See pages 77, 79.

[144] Erdal Arıkan. From sequential decoding to channel polarization and back again. *arXiv:1908.09594 [cs, math]*. See pages 77, 79.

[145] K. R. Narayanan and G. L. Stuber. A novel arq technique using the turbo coding principle. *IEEE Communications Letters*, 1(2):49–51, March 1997. See pages 77, 80.

[146] T. Rodrigues, R. D. Souza, and M. E. Pellenz. Hybrid arq scheme based on recursive convolutional codes and turbo decoding. In *2007 IEEE International Conference on Communications*, pages 995–1000, June 2007. See pages 77, 80.

[147] 3GPP. 3rd generation partnership project; technical specification group radio access network; evolved universal terrestrial radio access (e-utra);

multiplexing and channel coding (release 10). 3gpp ts 36.212, Dec 2010. See pages 77, 80.

[148] Y. Fang, G. Bi, Y. L. Guan, and F. C. M. Lau. A survey on protograph LDPC codes and their applications. *IEEE Communications Surveys Tutorials*, 17(4):1989–2016. See page 78.

[149] H. Li, B. Bai, X. Mu, J. Zhang, and H. Xu. Algebra-assisted construction of quasi-cyclic LDPC codes for 5g new radio. *IEEE Access*, 6:50229–50244. See pages 78, 79.

[150] A. Abbasfar, D. Divsalar, and K. Yao. Accumulate-repeat-accumulate codes. *IEEE Transactions on Communications*, 55(4):692–702. See page 78.

[151] S. Abu-Surra, D. Divsalar, and W. E. Ryan. Enumerators for protograph-based ensembles of LDPC and generalized LDPC codes. *IEEE Transactions on Information Theory*, 57(2):858–886. See page 78.

[152] Ken R. Duffy, Amit Solomon, Kishori M. Konwar, and Muriel Médard. 5g NR CA-polar maximum likelihood decoding by GRAND. In *2020 54th Annual Conference on Information Sciences and Systems (CISS)*, pages 1–5. See page 79.

[153] Yasantha Samarawickrama and Victor Cionca. Impact of pilot lengths of psam on polar code performance in ricean fading for realistic industrial channels. In *2021 International Conference on COMmunication Systems NETworkS (COMSNETS)*, pages 525–530, Jan 2021. See pages 79, 82.

[154] Yasantha Samarawickrama, Victor Cionca, Susan Rea, and Alan McGibney. Optimization of polar code designs for industrial wireless communications. In *2021 International Conference on COMmunication Systems NETworkS (COMSNETS)*, pages 363–365, Jan 2021. See pages 79, 82.

[155] H. Chen, R. G. Maunder, and L. Hanzo. A survey and tutorial on low-complexity turbo coding techniques and a holistic hybrid arq design example. *IEEE Communications Surveys Tutorials*, 15(4):1546–1566, Fourth 2013. See page 80.

[156] T. Kailath. A general likelihood-ratio formula for random signals in gaussian noise. *IEEE Trans. Inf. Theor.*, 15(3):350–361, September 2006. See page 82.

[157] C. Husmann, P. C. Nikolaou, and K. Nikitopoulos. Reduced latency ML polar decoding via multiple sphere-decoding tree searches. *IEEE Transactions on Vehicular Technology*, 67(2):1835–1839. See pages 83, 85, and 87.

[158] Komal Arora, Jaswinder Singh, and Yogeshwar Singh Randhawa. A survey on channel coding techniques for 5g wireless networks. *Telecommun Syst*, 73(4):637–663. See page 83.

[159] Robert G. Maunder. A fully-parallel turbo decoding algorithm. *IEEE Transactions on Communications*, 63(8):2762–2775. See pages 83, 85, 88, and 93.

[160] Fully parallel FPGA decoder for irregular LDPC codes. See pages 83, 86.

[161] A. Balatsoukas-Stimming and A. Dollas. FPGA-based design and implementation of a multi-GBPS LDPC decoder. In *22nd International Conference on Field Programmable Logic and Applications (FPL)*, pages 262–269. ISSN: 1946-1488. See pages 83, 84, and 86.

[162] Haoran Li, Youn Sung Park, and Zhengya Zhang. Reconfigurable architecture and automated design flow for rapid FPGA-based LDPC code emulation. In *Proceedings of the ACM/SIGDA international symposium on Field Programmable Gate Arrays - FPGA '12*, page 167. ACM Press. See pages 83, 84, 86, and 93.

[163] S. Yeşil and M. Arslan. Dual port ram based layered decoding for multi rate quasi-cyclic LDPC codes. In *2014 12th International Conference on Signal Processing (ICSP)*, pages 1524–1530. ISSN: 2164-523X. See pages 83, 86.

[164] S. Yen, S. Hung, C. Chen, H. Chang, S. Jou, and C. Lee. A 5.79-gb/s energy-efficient multirate LDPC codec chip for IEEE 802.15.3c applications. *IEEE Journal of Solid-State Circuits*, 47(9):2246–2257. See pages 83, 86.

[165] Y. S. Park, D. Blaauw, D. Sylvester, and Z. Zhang. Low-power high-throughput LDPC decoder using non-refresh embedded DRAM. *IEEE Journal of Solid-State Circuits*, 49(3):783–794. See pages 84, 86.

[166] B. Xiang, D. Bao, S. Huang, and X. Zeng. An 847–955 mb/s 342–397 mW dual-path fully-overlapped QC-LDPC decoder for WiMAX system in 0.13 μ m CMOS. *IEEE Journal of Solid-State Circuits*, 46(6):1416–1432. See pages 84, 86.

[167] Vikram Arkalgud Chandrasetty and Syed Mahfuzul Aziz. Resource efficient LDPC decoders for multimedia communication. *Integration*, 48:213–220. See pages 84, 86.

[168] V. L. Petrović, M. M. Marković, D. M. E. Mezeni, L. V. Saranovac, and A. Radošević. Flexible high throughput QC-LDPC decoder with perfect pipeline conflicts resolution and efficient hardware utilization. *IEEE Transactions on Circuits and Systems I: Regular Papers*, 67(12):5454–5467. See pages 84, 86.

[169] Yin Xu, Leszek Szczecinski, Bo Rong, Fabrice Labeau, Dazhi He, Yiyan Wu, and Wenjun Zhang. Variable llr scaling in min-sum decoding for irregular ldpc codes. *IEEE Transactions on Broadcasting*, 60(4):606–613, Dec 2014. See page 84.

[170] D. Kam, H. Yoo, and Y. Lee. Ultralow-latency successive cancellation polar decoding architecture using tree-level parallelism. *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, pages 1–12. See pages 84, 86.

[171] F. Ercan, C. Condo, and W. J. Gross. Reduced-memory high-throughput fast-SSC polar code decoder architecture. In *2017 IEEE International Workshop on Signal Processing Systems (SiPS)*, pages 1–6. ISSN: 2374-7390. See pages 84, 87.

[172] C. Leroux, A. J. Raymond, G. Sarkis, and W. J. Gross. A semi-parallel successive-cancellation decoder for polar codes. *IEEE Transactions on Signal Processing*, 61(2):289–299. See pages 84, 86.

[173] B. Yuan and K. K. Parhi. Low-latency successive-cancellation polar decoder architectures using 2-bit decoding. *IEEE Transactions on Circuits and Systems I: Regular Papers*, 61(4):1241–1254. See pages 84, 86.

[174] Pascal Giard, Alexios Balatsoukas-Stimming, Gabi Sarkis, Claude Thibeault, and Warren J. Gross. Fast low-complexity decoders for low-rate polar codes. *J Sign Process Syst*, 90(5):675–685. See page 84.

[175] B. Yuan and K. K. Parhi. Low-latency successive-cancellation list decoders for polar codes with multibit decision. *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, 23(10):2268–2280. See pages 84, 87.

[176] A. Balatsoukas-Stimming, A. J. Raymond, W. J. Gross, and A. Burg. Hardware architecture for list successive cancellation decoding of

polar codes. *IEEE Transactions on Circuits and Systems II: Express Briefs*, 61(8):609–613. See pages 84, 87.

[177] Chenrong Xiong, Jun Lin, and Zhiyuan Yan. A multi-mode area-efficient SCL polar decoder. *arXiv:1510.07510 [cs, math]*. See pages 84, 87.

[178] J. Lin and Z. Yan. An efficient list decoder architecture for polar codes. *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, 23(11):2508–2518. See pages 84, 87.

[179] YouZhe Fan, ChenYang Xia, Ji Chen, Chi-Ying Tsui, Jie Jin, Hui Shen, and Bin Li. A low-latency list successive-cancellation decoding implementation for polar codes. *IEEE Journal on Selected Areas in Communications*, 34(2):303–317. See pages 84, 87, and 93.

[180] F. Ercan, T. Tonnellier, N. Doan, and W. J. Gross. Practical dynamic SC-flip polar decoders: Algorithm and implementation. *IEEE Transactions on Signal Processing*, 68:5441–5456. See pages 85, 87.

[181] J. Piao, J. Dai, and K. Niu. CRC-aided sphere decoding for short polar codes. *IEEE Communications Letters*, 23(2):210–213. See pages 85, 87.

[182] S. A. Hashemi, C. Condo, and W. J. Gross. A fast polar code list decoder architecture based on sphere decoding. *IEEE Transactions on Circuits and Systems I: Regular Papers*, 63(12):2368–2380. See pages 85, 87.

[183] S. Tajima, T. Takahashi, S. Ibi, and S. Sampei. Iterative decoding based on concatenated belief propagation for CRC-aided polar codes. In *2018 Asia-Pacific Signal and Information Processing Association Annual Summit and Conference (APSIPA ASC)*, pages 1411–1415. ISSN: 2640-0103. See pages 85, 87.

[184] B. Bougard, A. Giulietti, V. Derudder, J.-W. Weijers, S. Dupont, L. Hollevoet, F. Catthoor, L. Van der Perre, H. De Man, and R. Lauwereins. A scalable 8.7nj/bit 75.6mb/s parallel concatenated convolutional (turbo-) CODEC. In *2003 IEEE International Solid-State Circuits Conference, 2003. Digest of Technical Papers. ISSCC.*, pages 152–484 vol.1. ISSN: 0193-6530. See pages 85, 88.

[185] Cheng-Chi Wong, Yung-Yu Lee, and Hsie-Chia Chang. A 188-size 2.1mm2 reconfigurable turbo decoder chip with parallel architecture for 3gpp LTE system. In *2009 Symposium on VLSI Circuits*, pages 288–289. ISSN: 2158-5636. See pages 85, 88.

[186] Luping Xiang, Matthew F. Brejza, Robert G. Maunder, Bashir M. Al-Hashimi, and Lajos Hanzo. Arbitrarily parallel turbo decoding for ultra-reliable low latency communication in 3gpp LTE. *IEEE Journal on Selected Areas in Communications*, 37(4):826–838. See pages 85, 88.

[187] Myoungcheol Shin, Incheol Park, and Senior Member. SIMD processor-based turbo decoder supporting multiple third-generation wireless standards. *IEEE Trans. on VLSI*, pages 801–810. See pages 85, 88.

[188] ZTE Corp. Throughput and latency analysis on new channel coding candidates for NR. See pages 85, 87, and 93.

[189] Ethan Liang, Hengjie Yang, Dariush Divsalar, and Richard D. Wesel. List-decoded tail-biting convolutional codes with distance-spectrum optimal CRCS for 5g. In *2019 IEEE Global Communications Conference (GLOBECOM)*, pages 1–6. IEEE. See pages 85, 88.

[190] X. Wang, H. Qian, J. Xu, Y. Yang, and F. Wang. An efficient CVA-based decoding algorithm for tail-biting codes. In *2011 IEEE Global Telecommunications Conference - GLOBECOM 2011*, pages 1–5. ISSN: 1930-529X. See pages 85, 87.

[191] H. Zhou, W. J. Gross, Z. Zhang, X. You, and C. Zhang. Efficient sphere polar decoding via synchronous determination. *IEEE Transactions on Vehicular Technology*, 69(6):6777–6781. See pages 85, 87.

[192] InterDigital Inc. Channel codes for pbch. 3GPP TSG RAN WG1 89 R1-1708359. See page 90.

[193] Dereje Assefa Wassie, Ignacio Rodriguez, Gilberto Berardinelli, Fernando M. L. Tavares, Troels B. Sorensen, and Preben Mogensen. Radio propagation analysis of industrial scenarios within the context of ultra-reliable communication. In *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*, pages 1–6, 2018. See page 96.

[194] Mustafa Cemil Coşkun, Giuseppe Durisi, Thomas Jerkovits, Gianluigi Liva, William Ryan, Brian Stein, and Fabian Steiner. Efficient error-correcting codes in the short blocklength regime. *arXiv:1812.08562 [cs, math]*. See page 96.

[195] Evgeny Khorov, Anton Kiryanov, Andrey Lyakhov, and Giuseppe Bianchi. A tutorial on ieee 802.11ax high efficiency wlans. *IEEE Communications Surveys & Tutorials*, 21(1):197–216, 2019. See pages 97, 113, and 120.

[196] Jingya Yang, Bo Ai, Ilsun You, Muhammad Imran, Longhe Wang, Ke Guan, Danping He, Zhangdui Zhong, and Wilhelm Keusgen. Ultra-reliable communications for industrial internet of things: Design considerations and channel modeling. *IEEE Network*, 33(4):104–111, 2019. See page 116.

[197] Adnan Aijaz and Mahesh Sooriyabandara. The tactile internet for industries: A review. *Proceedings of the IEEE*, 107(2):414–435, 2019. See pages 117, 124, and 131.

[198] Theodore Rappaport. *Wireless Communications: Principles and Practice*. Prentice Hall PTR, USA, 2nd edition, 2001. See pages 119, 129.