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Medium Access Control Protocols for Improving Data Communication Reliability in PLC Systems

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To my mother Vanda
To my father Roberto
To my grandmother Maria
To my fiancée Gabriela
To my uncles Cosme and Luiz Carlos
To my aunt Sônia
To my cousin Kalina

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Primeiramente, eu agradeço à minha mãe, Vanda, que vem sobrevivendo como uma guerreira, me dando, diariamente, exemplos de superação, de perseverança, de esperança e de força de vontade. Juntamente com minha querida mãe, devo agradecer ao meu falecido pai, Roberto, e à minha falecida avó, Maria, que sempre me apoiaram incondicionalmente, de modo a possibilitar que eu me tornasse quem sou. Quero e devo, também, agradecer à minha noiva Gabriela, por sua companhia, paciência, carinho e apoio, sempre se mantendo ao meu lado em todos os momentos. Ao meu tio Cosme, que me deu o maior dos presentes: a oportunidade de ter uma boa educação. Ao meu tio Luiz Carlos, à minha tia Sônia e à minha prima Kalina, que sempre estão presentes e me ajudam nos momentos mais críticos. Ao meu orientador, Moisés, que foi paciente e humano, abrindo exceções e me apoiando diante da difícil situação em que me encontro, sempre acreditando no meu trabalho. Ao meu coorientador, Alex, pela paciência e apoio. A todos aqueles que, de alguma forma, estiveram presentes, direta ou indiretamente, e colaboraram para que essa etapa fosse concluída.

“A new idea comes suddenly and in a rather intuitive way.
But intuition is nothing but the outcome of earlier intellectual experience.”

Albert Einstein

RESUMO

A presente tese apresenta uma pesquisa abrangente sobre o estado da arte dos protocolos de controle de acesso ao meio (MAC) para sistemas de comunicação de dados via rede elétrica (PLC), incluindo uma visão geral dos resultados de pesquisa e uma organização dos atuais protocolos MAC para sistemas PLC em termos de tipos de protocolos, aplicações e principais focos de pesquisa. Ademais, são apresentadas tecnologias e padrões modernos de PLC, destacando suas características de subcamada MAC e fornecendo uma análise comparativa detalhada de protocolos MAC no contexto de aplicações atuais e emergentes para PLC. Em seguida, as tendências futuras são identificadas no escopo da subcamada MAC para sistemas PLC, com o objetivo de estimular esforços adicionais de pesquisa nesse contexto. Além disso, a presente tese propõe uma abordagem genérica que pode melhorar a confiabilidade da comunicação de dados através de correções de pacotes no nível da camada de enlace. Com base nesta abordagem genérica, a presente tese também propõe o EPLC-CMAC, um protocolo MAC cooperativo aprimorado para sistemas PLC de banda-larga para ambientes *indoor*. Mais especificamente, o EPLC-CMAC realiza retransmissões cooperativas para auxiliar na comunicação de dados entre um nó fonte e um nó destino. No caso de uma falha de retransmissão, o nó destino usa cópias corrompidas dos pacotes transmitidos e retransmitidos, que estão armazenados em seu *buffer*, para detectar e corrigir os bits errados. Resultados numéricos mostram que o uso do EPLC-CMAC é capaz de reduzir a taxa de perda de pacotes mesmo durante ruídos impulsivos, melhorando a confiabilidade da comunicação de dados dos cenários considerados. Finalmente, a presente tese propõe o EHCMAC, um protocolo MAC cooperativo aprimorado para sistemas híbridos PLC-sem fio de banda larga para ambientes *indoor*. Após transmissões malsucedidas, o EHCMAC tenta corrigir pacotes corrompidos, na camada de enlace, antes de executar a solicitação de retransmissão. Caso essa correção falhe, o EHCMAC realiza retransmissões cooperativas e, quando tais retransmissões não são suficientes para garantir uma comunicação bem-sucedida, uma segunda tentativa de correção de pacote é aplicada na camada de enlace. A avaliação de desempenho do protocolo EHCMAC é realizada através da comparação de sistemas de comunicações híbridos PLC-sem fio de banda-larga para ambientes *indoor* que consideram utilização do protocolo proposto com sistemas semelhantes que não consideram a utilização do mesmo. Resultados numéricos e teóricos mostram que o uso do protocolo proposto é capaz de reduzir notavelmente a necessidade de retransmissões e a taxa de perda de pacotes. Mais especificamente, à medida que a taxa de erros de bit na camada de enlace diminui, esses resultados tendem a zero mais rápido quando o protocolo EHCMAC é considerado.

Palavras-chave: Comunicação via rede elétrica. Controle de acesso ao meio. Protocolos de cooperação. Técnicas de correção de pacotes. Confiabilidade.

ABSTRACT

The present thesis provides a comprehensive survey regarding the state of the art of medium access control (MAC) protocols for power line communication (PLC) systems, including an overview of existing PLC MAC research results and an organization of current PLC MAC protocols in terms of type of protocols, applications, and main research focus. Moreover, the survey presents modern PLC technologies and standards, highlighting their MAC sublayer characteristics and providing a detailed comparative analysis of PLC MAC protocols in the context of current and emerging PLC applications. Then, future trends are identified within the scope of the MAC sublayer for PLC systems with a view to stimulating additional research efforts on PLC MAC design. In addition, the present thesis proposes a generic approach that may improve the data communication reliability through packet corrections at the link layer level. Based on this generic approach, the present thesis also proposes EPLC-CMAC, an enhanced cooperative MAC protocol for in-home broadband PLC systems. More specifically, the cooperative protocol performs relayed retransmissions according to the relay availability, for assisting data communication between source and destination nodes. In case a packet retransmission fails, the destination node uses corrupted copies from the transmitted and the retransmitted packets, which are stored in its buffer, to detect and correct the erroneous bits. Numeric results show that the use of the EPLC-CMAC protocol is capable of reducing the packet loss ratio even during impulsive noises, improving the data communication reliability of the considered scenarios. Finally, but not the least, the present thesis propose EHCMAC, an enhanced cooperative MAC protocol for in-home broadband hybrid PLC-wireless systems. After unsuccessful transmissions, the EHCMAC protocol tries to correct corrupted packets, at the link layer, before performing the retransmission request. In case this correction fails, the EHCMAC protocol exploits relay availability for retransmitting packets and, when the relay assistance is not enough to ensure successful retransmission, a second packet correction attempt is applied at the link layer. The performance evaluation of the EHCMAC protocol is accomplished by comparing in-home broadband hybrid power line communication-wireless systems that consider the use of the proposed protocol with in-home broadband hybrid power line communication-wireless systems in which the proposed protocol is not considered. Numerical and theoretical results show that the use of the proposed protocol is capable of remarkably reducing the need for packet retransmissions and the packet loss ratio. More specifically, as the bit error ratio at the link layer decreases, these results tend to zero faster when the EHCMAC protocol is considered.

Key-words: Power line communication. Medium access control. Cooperative protocols. Packet correction techniques. Reliability.

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

ACK acknowledgment

AF amplify-and-forward

AMI advanced metering infrastructure

AMR automatic meter reading

ARQ automatic repeat request

BB broadband

BER bit error rate

BFS brute force search

BPLC broadband PLC

CFIFS contention-free inter frame space

CMAC cooperative medium access control

CMP Coexisting MAC protocol

CRC cyclic redundancy checking

CSMA carrier sense multiple access

CSMA/CA carrier sense multiple access/collision avoidance

CSMA/CD carrier sense multiple access/collision detection

CW contention window

DF decode-and-forward

DP data period

EMI electromagnetic interference

FEC forward error correction

HDTV high-definition television

HEMS Home Energy Management System

IoT internet of things

ITC Impossible to Cooperate

ITU international telecommunication union

MAC medium access control

MOFDM multi-band orthogonal frequency division multiplex

MPDU medium access control protocol data unit

MV Majority Voting

NACK negative acknowledgement

NB narrowband

NB-PLC narrowband PLC

NOMA non-orthogonal multiple access

OFDM orthogonal frequency division multiplexing

OFDMA orthogonal frequency division multiple access

PER packet error rate

PKT packet

PLC power line communication

QoS quality of service

SNR signal-to-noise ratio

SP signaling period

TDM Time Division MAC

TDMA time division multiple access

VoIP voice over internet protocol

VSMA virtual slot multiple access

WTC Want to Cooperate

XOR exclusive OR

CONTENTS

1 INTRODUCTION

In the literature, data communication is commonly defined as any process that enables the exchanging of information of any nature from a sender to one or more receivers in any usable form by means of any electromagnetic system [1]. This concept, which has been severally explored since the beginning of the 19th century [2], is still in continuous evolution. In the present days, data communication systems are responsible for interconnecting people and companies, breaking localization boundaries, spreading information and knowledge from limitless sources all around the world. In January 2019, for instance, there were more than 4 billion internet users worldwide, which can be compared to more than 3 billion users recorded at the end of 2016 [3].

Historically, the initial development of patents and researches to enable the data communication date back to the year of 1837 [1] in which Samuel Morse exhibited a working telegraph system that was capable of transmitting electrical signals over a wire laid between stations. The same inventor, developed a code, bearing his name, that allowed the simple transmission of complex messages across telegraph lines. This code is still a research subject nowadays [4]. The telegraph invention, nevertheless, was patented by Charles Wheatstone in the same year [5].

Later, in 1876, Alexander Graham Bell improved the telegraph conceiving the Telephone system, which allowed voice transmissions through a wired medium [6]. Then, in 1895, Guglielmo Marconi developed the first successful long-distance wireless telegraph [7]. Six years later, in 1901, the first transatlantic radio signal was broadcasted, ending with the isolation inherent to oceanic travels until this date [8]. During the first world war, wireless radio communication systems received substantial attention for military purposes and, in the early 1920s, the first commercial radio voice broadcasts were launched [9].

In 1958, in the context of the cold war, the United States launched a communication-oriented satellite greatly expanding the data communication possibilities [10]. In 1962, the first fax transmission was performed and the modulation of data into sound for telephone communication spread its popularity for the rest of the century [11]. In the same decade, in 1969, the development of the Internet Protocol marked one of the most significant milestones in the data communication history so that in 1991 more than a million of servers had come online by using such protocol [12]. In this context, the World Wide Web emerged as the primary internet component [13]. In parallel, in 1974 the Federal Communication Commission of the United States began allocating wireless spectrums for wireless communication purposes [14].

The wireless technology is in continuous evolution among several important applications used in the present days, offering mobility and a simple infrastructure independent of the excess of cables. Different types of wireless communication include satellite [15], optical (e.g., infrared, visible light, ultraviolet) [16], radio [17], Wi-Fi [18] and mobile, such as $5G$ [19], among others. This variety of wireless types enable a set of important applications such as the use of mobile telephones [20], sensor networks [21], local area networks [22], to name a few.

A common feature among the aforementioned technologies is the challenge of interconnecting as many places, people and devices as possible. In this context, an emerging data communication technology, known as power line communication (PLC), has been earning prominence. Such technology uses the ubiquitous electrical wiring infrastructure for data communication purposes. This electrical wiring infrastructure will cover almost 89% of the global population in 2019 according to [23]. Furthermore, PLC has been attracting worldwide interests because of the needs and demands related to emergent and heavily dependable data communication applications, such as Smart Grid, in-vehicle, in-home data communication and the internet of things (IoT) [24–30]. For instance, regarding in-vehicle systems, PLC is very attractive since it provides an additional data communication path, while increasing reliability due to the low number of connections and reducing manufacturing and operative costs related to the weight of unnecessary additional cabling [31, 32].

The use of electric power grids as a data communication medium has been known since the beginning of the $20th$ century. Initially, PLC was employed in narrowband (NB) or low data rate technologies, such as remote meter reading and telephonic communications [33]. Recently, multimedia and in-vehicle (aircraft, car, ship and spacecraft) applications have been motivating research on broadband (BB), or high speed PLC. PLC systems have already been successfully adopted in key applications such as: smart grid [34–36], smart home [37–39], in-vehicle data networks [40–42], high-speed network [43], home area network [44–46], smart metering [47, 48], multimedia and access data network [49–51].

Regardless of the applications, widely used PLC standards, such as HomePlug [52], IEEE 1901 [53], IEEE 1901.2 [54], ITU.T G.hn [55] and ITU-T G.hnem [56] focus their specifications on physical and link layers. These layers are totally related to the data communication medium, while the upper layers are oriented for establishing and managing the data network. The physical layer addresses the modulation and encapsulation of information for its reliable transmission through the data communication medium, while the link layer has three main functions: multiple access, resource sharing and traffic control [57].

In this context, PLC research efforts have been largely focused on the physical layer due to the complexity of electric power systems and the challenges to their use as a data communication medium. For example, there are the dynamics and diversity of loads (e.g., time-frequency varying behavior [58, 59]; remarkable signal attenuation when frequency or distance increase(s); impedance mismatching at the points of connection among power lines, loads and transceivers [60]; high power impulsive noises yielded by connecting and disconnecting loads, equipment and alternate current/direct current (AC/DC) converters [61–63]; electromagnetic interference due to the use of unshielded power lines and coupling problems [64, 65]); restrictive regulatory constraint on electric field irradiation. To address some of these issues, the PLC community is consistently developing advanced tools, techniques, methods and approaches [66–68]. For instance, [69, 70] and [71–73] proposed, respectively, cooperative protocols and resource allocation techniques to improve PLC system performance at the physical layer to handle some of these issues. Moreover, [28, 74–80] investigated hybrid data communication media, which involves PLC and wireless channels, aiming to improve performance (data-rate and reliability) at the physical layer.

On the other hand, relevant data communication features are related to the medium access control (MAC) sublayer. For example, unfairness of resource allocation [81], starvation [82], collisions [50] and channel access delay [83] may affect users' satisfaction, system performance and reliability at upper layers. Therefore, it is important to deeply study MAC protocols in order to deal with these features more effectively [84]. In fact, MAC protocols are capable of reinforcing PLC system reliability and performance [85, 86] and guaranteeing quality of service (QoS) [87].

1.1 OBJECTIVES

Based on the aforementioned context the main objectives of the present thesis are as follows:

- To introduce a survey on the literature regarding PLC MAC protocols. This survey will focus on organizing these protocols according to their characteristics and to well-established terminologies in the PLC community; presenting the main PLC technologies and standards in the link layer perspective; discussing each protocol in the scope of emerging PLC applications; identifying future trends and open research issues.

- To propose a generic approach that considers the use of packet correction attempts at the link layer level so that the legacy of standardized physical layers may be preserved. This proposal will focus on improving data communication reliability when preexistent techniques and protocols are not enough to avoid retransmission requests or packet losses.

- Based on the aforementioned generic approach, to outline MAC protocols for improving the data communication reliability of PLC systems and hybrid PLC-wireless systems. More specifically, these protocols will focus on the use of a cooperative

MAC protocol together with packet correction techniques, at the link layer level, aiming to avoid retransmission requests or packet losses.

1.2 THESIS OUTLINE AND MAIN CONTRIBUTIONS

The present thesis is organized as follows:

- Chapter 2 presents a survey on the literature related to MAC protocols for PLC systems. This chapter organizes, discusses and identifies future trends and open research issues regarding PLC MAC protocols in the scope of emergent PLC applications.
- Chapter 3 identifies a problem that may occur when physical layer techniques and protocols are not enough to ensure a reliable data communication. In this case, retransmissions and packet losses may occur. In order to avoid this problem, the main contribution of this chapter is to propose an extra step of packet correction at the link layer level. This chapter also discusses failure causes and probabilities related to the proposed approach.
- Chapters 4 proposes, based on Chapter 3, the EPLC-CMAC protocol, which merges a cooperative MAC protocol with a packet correction technique at the link layer level of PLC systems. This chapter also discusses failure causes and probabilities related to the proposed protocol. Numerical results show that the EPLC-CMAC protocol is capable of reducing packet loss ratio even during impulsive noises.
- Chapters 5 proposes, based on Chapter 3, the EHCMAC protocol, which merges a cooperative MAC protocol with packet correction techniques at the link layer level of hybrid PLC-wireless systems. This chapter also discusses failure causes and probabilities related to the proposed protocol. Theoretical and numerical results show that the EHCMAC protocol is capable of reducing the need for retransmission and even packet losses.

2 MEDIUM ACCESS CONTROL PROTOCOLS FOR POWER LINE COMMUNICATION: A SURVEY

Despite the variety of existing MAC protocols and their relevance for PLC systems, there is a lack of comprehensive analyses and discussions, in the literature, driving attention to PLC systems within the MAC sublayer perspective. Various surveys about PLC focus on subjects related to the physical layer [65, 88, 89], but these works do not provide information about appropriate PLC MAC protocols according to each PLC application and they do not emphasize data communication challenges related to the MAC sublayer perspective. While [90–92] provided a brief and interesting overview about the MAC sublayer of PLC system, the treatment was not thorough and the subjects were only briefly explored.

The present chapter offers a comprehensive survey about the MAC sublayer for PLC systems because it is one of the most important components of a PLC modem. In fact, having a big picture of PLC MAC protocols is of utmost importance to extend and stimulate researches for future improvements and to introduce new protocols that contribute to maximize the use of the electric power system infrastructure for data communication purpose. The aim is to pave the way for bringing researchers' attention to novel communication demands [93, 94] related to IoT, smart things, multimedia and in-vehicle applications. In order to establish a systematic presentation of several aspects related to PLC MAC protocols, the present chapter deals with the following contributions:

- An organization of PLC MAC protocols into contention-free, contention based, and hybrid. Moreover, these protocols are classified in terms of applications and main research focus.
- A description of the main PLC standards and their MAC sublayer characteristics. Additionally, PLC applications are analyzed, under the suggested organization perspective and their associated MAC protocols.
- A discussion of research opportunities, challenges and future trends related to PLC MAC protocols that can offer some guidance for researchers and practitioners in this field. These are very interesting issues, because the novelties related to IoT, smart things, multimedia and in-vehicular communications have to be studied in order to optimize the use of network resources in PLC systems.

In this sense, this chapter is organized as follows: Section 2.1 focuses on the suggested organization of PLC MAC protocols. Section 2.2 addresses PLC standards from a MAC sublayer perspective. Sections 2.3, 2.4 and 2.5 focus on Smart Things, multimedia and in-vehicular applications, respectively, while Section 2.6 addresses future trends and potential research issues. Finally, Section 2.7 provides a summary of the present chapter.

2.1 PLC MAC PROTOCOLS ORGANIZATION

MAC protocols are often associated with MAC methods to perform several functionalities, such as multiple access, resource sharing and traffic control [57]. According to [66], a MAC method (e.g., time division multiple access (TDMA)) divides the transmission resources into accessible sections, which can be used for multiple users. In this sense, MAC protocols represent specific resource sharing strategies, which focus on organizing the access of these multiple users to the shared medium.

2.1.1 Organization based on Frequency Bands

Based on PLC MAC protocols characteristics [43] and on well-established terminologies in the PLC community, it is possible to offer the organization presented in Figure 1. In this figure, initially, MAC protocols are organized into NB (low-bit-rate) and BB (high-bit-rate) PLC technologies [147] due to the fact that both of them demand distinct solutions of their MAC sublayers in terms of requirements of the associated applications. These applications are in accord with the PLC terminology for narrowband and broadband PLC systems that do not follow the usual definition of narrowband and broadband in the communications field. As a matter of fact, narrowband PLC (NB-PLC) works at lower frequencies (e.g., below 500 kHz [54]), lower bit-rates (i.e., kbps), and can be used in short and long-distance applications (up to a hundred of Km [148]). On the other hand, broadband PLC (BPLC) works at higher frequencies (e.g., from 1.7 MHz up to 100 MHz [53]), high-bit-rates (i.e., several Mbps) and can only be used in short distance applications (less than 200 meters without repeaters). In fact, the disparity between NB and BB characteristics reveal distinct sets of features to be fulfilled by PLC MAC protocols.

More specifically, [27] presents NB-PLC systems characteristics and advantages under certain scenarios and applications. According to the author, such systems demand low-cost chipset as well as easy installation. In addition, NB-PLC systems do not generate significant electromagnetic interference (EMI), and, thus, they are recommended for long range and low-bit-rate applications. These advantages, and others pointed out in [148], have been inspiring the use of NB-PLC in smart grid applications [95], such as smart meters [48], smart homes [97] and in-vehicle [42].

2.1.2 Organization based on Channel Assignment and MAC Methods

Regarding each application, attention can be given to channel assignment methods, which gather contention-free, contention-based or hybrid MAC protocols for NB and BB

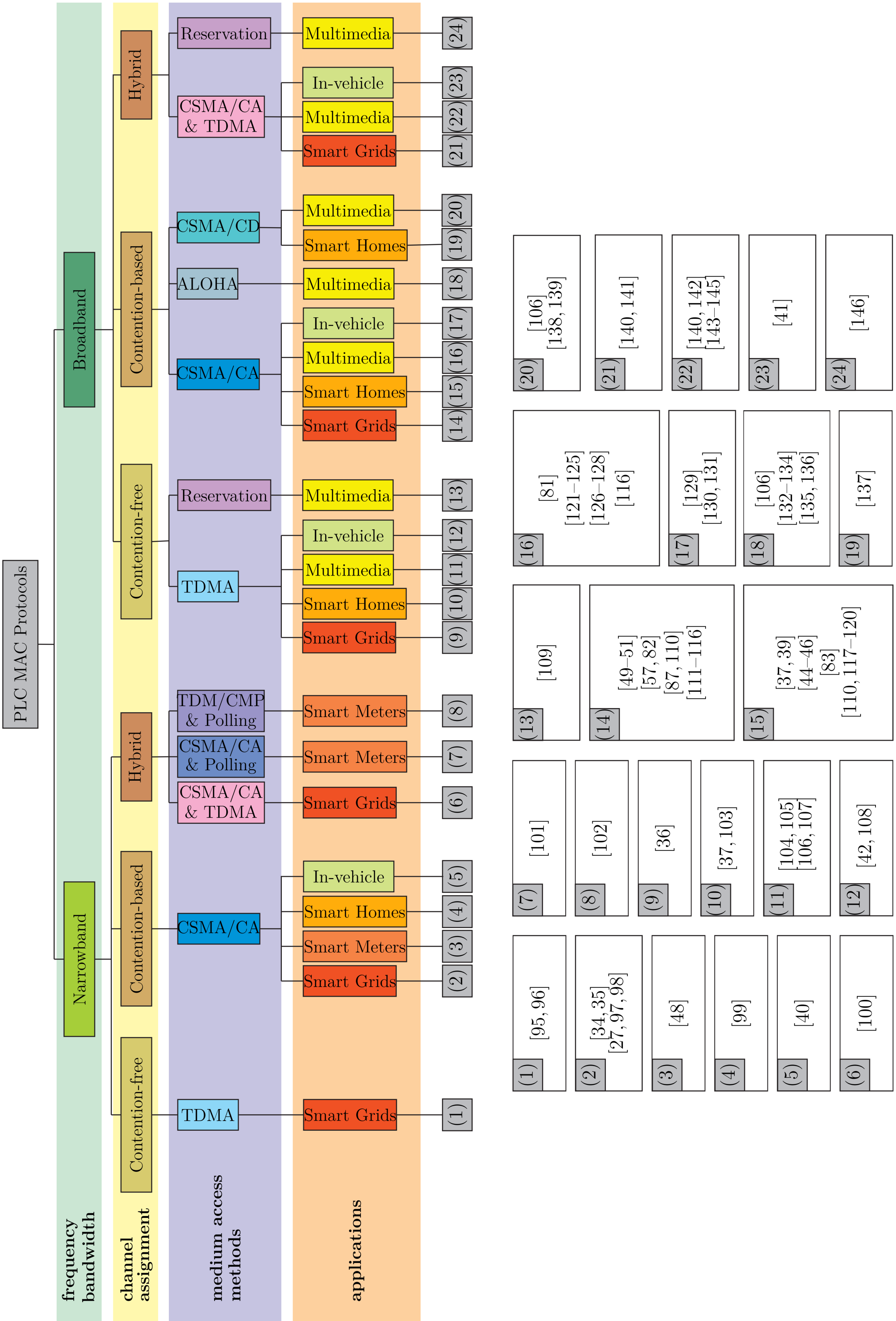


Figure 1: The organization of PLC MAC protocols.

applications:

- Contention-free protocols, such as the ones based on TDMA access method [95, 104, 105] and on polling-based protocols [101, 102]. These protocols are more suitable for data networks with bounded access delay (e.g., QoS requirements) and for multimedia applications, because they have a predictable round-trip time. However, contention-free protocols may be impaired by a difficult synchronization process, which may cause scheduling problems.

- Contention-based protocols, such as the ones based on carrier sense multiple access/collision avoidance (CSMA/CA) [27, 99, 110], CSMA/collision detection [138, 139] (CSMA/CD) and on ALOHA protocols [132–134]. These protocols are suitable for data networks that do not require central coordinators and for large scale non-saturated data networks, because only active users will contend for accessing communication channel and a random backoff procedure minimizes the effects of collisions. However, contention-based protocols may introduce starvation (e.g., low priority users may never win channel access when contending against high priority users) and, usually, saturated data networks significantly increase the collision rate.

- Hybrid protocols, such as the ones in HomePlug [149] and in IEEE 1901 [53]. These Standards address protocols in which desired QoS parameters may be achieved in a distributed manner. In fact, hybrid protocols take advantage of both contention-based and contention-free MAC protocols characteristics. In [102], the authors proposed two hybrid protocols based on Time Division MAC (TDM) and Coexisting MAC protocol (CMP) working together with polling. Additionally, they analyzed different approaches to deal with common problems related to hybrid protocols, such as design complexity and overheads of beacon generation.

2.1.3 Discussion of the Proposed Organization

Through Figure 1 it is possible to note, for instance, that different types of MAC protocols are associated with NB when compared to BB. For instance, TDMA-based MAC protocols were investigated for allowing contention-free channel assignment in NB applications while both Reservation and TDMA-based MAC protocols were in BB applications. This kind of comparison can bring attention to what have been investigated and to opportunities for investigating other kinds of MAC protocols according to demands of each application.

Based on Figure 1, Figure 2 shows that broadband PLC MAC protocols are more common in the literature. Furthermore, it is important to mention that PLC Standards, such as IEEE 1901.2010, HomePlug AV and ITU-T G.hn, work with CSMA/CA due to its lower channel access delay and lower synchronization demands when compared to other methods such as TDMA. Moreover, CSMA/CA is capable of performing dynamic assignment of users and it is suitable for decentralized data network topologies. Hence, contention-based protocols have been receiving more attention in the literature, as showed in Figures 3.a and 3.b, also based on Figure 1. However, these Standards also adopt TDMA, due to its deterministic round-trip time, in applications with strict QoS requirements. Nevertheless, both CSMA/CA and TDMA also have disadvantages, which must be considered.

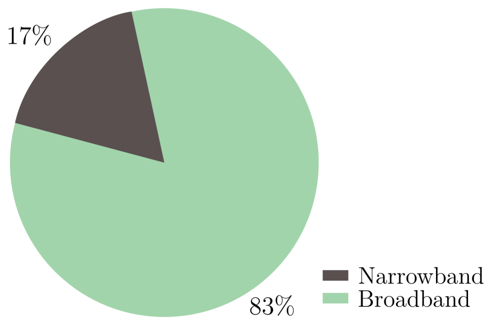
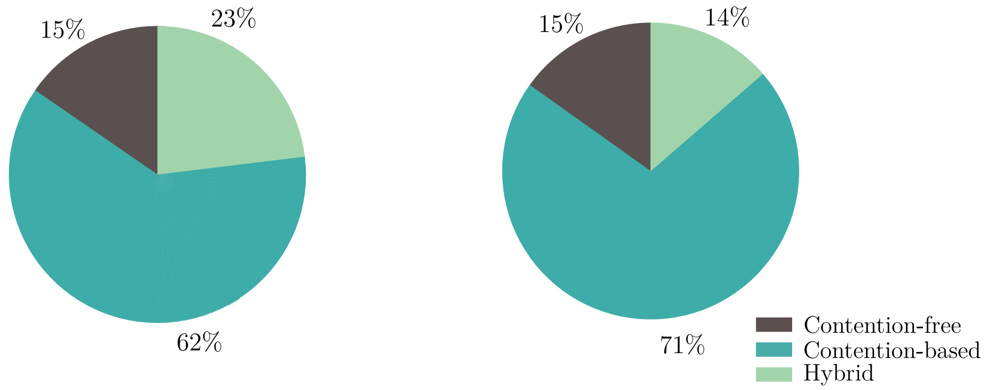


Figure 2: Frequency Bands of PLC MAC protocols.



(a) Narrowband (b) Broadband

Figure 3: Types of MAC protocols in narrowband and in broadband PLC systems

For the CSMA/CA, collisions and starvation are common problems. The former occurs when more than one user attempts to access the medium at the same time. Several works that focus on building and modifying backoff procedures to mitigate this problem are discussed. The latter is a common problem in saturated data networks considering priority-based protocols in which low priority users never obtain channel access over the high priority ones. Thus, priority-based schemes, mainly in saturated data networks, must have mechanisms to avoid this situation.

In the case of TDMA, one of its potential drawbacks occurs when there are idle users in a given frame. In this case, their time-slots will remain allocated, which represents a resource waste. Therefore, it seems to be necessary to associate the use of TDMA with appropriate MAC protocols in order to avoid such problems depending on the target application.

Other than CSMA/CA and TDMA, reservation-based protocols have been considered for designing the MAC sublayer of PLC systems [146, 150, 151]. This kind of protocol can offer fairness of resource sharing, QoS and robustness against noisy channels. However, the reservation of the channel for specific network nodes is usually performed by a central coordinator through the exchange of several control messages, which limits the topology of reservation-based applications.

2.1.4 Discussion about the Research Focus

Another perspective to organize PLC MAC protocols is in terms of their applications, as it is suggested in Figure 1. This kind of organization allows researchers to identify previous research in each application, which is a useful approach for starting a new application-oriented investigation. Based on the number of PLC MAC protocols, from the literature, related to each application, which are also organized in Figure 1, the percentages presented in Figure 4 are evaluated, which show that multimedia is the most common application using these protocols.

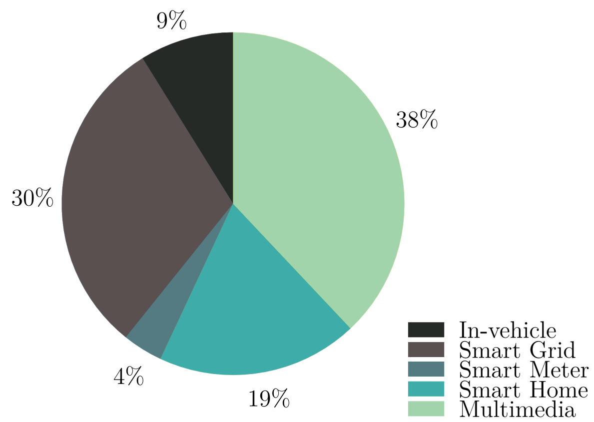


Figure 4: Main applications of PLC MAC protocols.

Lastly, Table 1 groups research related to PLC MAC protocols according to their main focus. Based on the works grouped in each row of this table, it was possible to evaluate the percentages presented in Figure 5, which show that the majority of works related to contention-free, contention-based and hybrid PLC MAC protocols aims at improving throughput and at reducing delay, respectively. Research that focus on backoff contention window (CW) adjustments and collision problems are often related to CSMA/CA. Fairness occurs when the medium is equitably shared among active network nodes, which is strictly related to MAC methods and MAC protocols. Works that address packet loss rate are commonly associated with performance analysis, together with throughput. There are also works proposing MAC frame formats other than the ones from PLC Standards and some works that focus on jitter and latency because they are important QoS parameters for real time applications (e.g., multimedia applications such as video streaming). Energy efficiency related works are typically associated with contention-based protocols in which only active nodes contend for the medium. Lastly, it was found a work that analyzes buffer management and starvation in a priority-based scheme adopted in a contention-based MAC protocol.

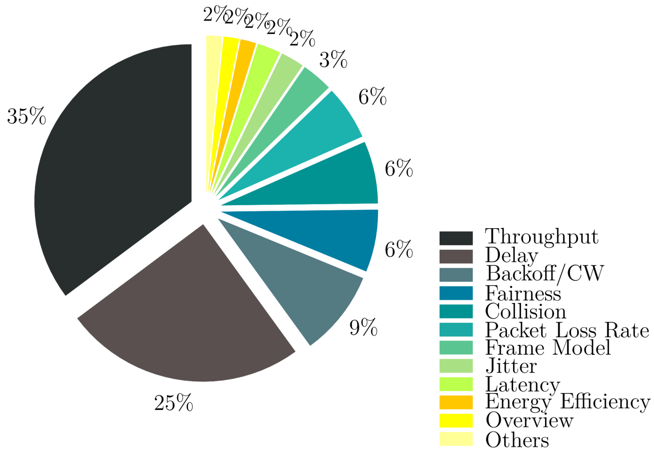


Figure 5: Main focus of PLC MAC protocols.

Table 1: The main research focus related to PLC MAC protocols.

Research Focus	**Related Works**
Throughput	[27, 34–37, 39, 40, 44–50, 95, 96, 99, 100, 102, 105–107, 109, 110] [112–115, 117–120, 122, 123, 125–128, 132, 137–139, 141–144] [146, 152]
Delay	[27, 34, 36, 40, 43, 45–49, 57, 87, 100–102, 106, 107, 110, 111, 113] [131–136, 141–144, 146]
Backoff/CW	[27, 50, 51, 83, 100, 110, 116, 123, 124, 143, 153]
Fairness	[27, 34, 44, 81, 99, 119, 120, 152]
Collision	[40, 41, 100, 110, 120–122, 127–131]
Packet Loss Rate	[37, 48, 98, 106, 113, 121, 122]
Frame Model	[38, 103, 154]
Jitter	[39, 87, 111]
Latency	[39, 104]
Energy Efficiency	[42, 97, 108]
Overview	[140, 145]
Buffer Management	[82]
Starvation	[82]

2.2 MAC PROTOCOLS IN PLC STANDARDS AND TECHNOLOGIES

The most studied PLC applications regarding MAC protocols (see Figure 1) are, generally, based on established PLC standards. This is because standards may provide coexistence or interconnection among new and preexistent technologies. For instance, NB-PLC system applications are relatively new and, so, they need to make use of mechanisms to coexist with preexistent technologies. Thus, the international telecommunication union (ITU), IEEE societies and other alliances have been investing in NB-PLC standards, such as IEEE 1901.2 [54], which involves players like G3-PLC Alliance [155]; ITU-T G.hnem [56]; PRIME [156], developed by the the PRIME Alliance [157].

Different from NB-PLC systems, BPLC systems [158] operate in a wider frequency bandwidth and, as a consequence, they achieve much higher bit-rates. Thus, applications such as multimedia [104], in-home internet service [45], indoor data network [140] and some smart grid applications [36] use BPLC systems.

In this context, in the year of 2001, the HomePlug Powerline Alliance released the HomePlug 1.0 Standard [52], which is capable of supporting a raw transmission rate up to 14 Mbps. Later, in 2005, the HomePlug Powerline Alliance published a high-speed PLC technology supporting up to 200 Mbps, namely Homeplug AV [149]. In the same year, a working group of IEEE initiated a project aimed at the unification of power line technologies in a single standard named as IEEE 1901 [53], which addressed both in-home and access broadband applications [159, 160]. In 2006, ITU-T started the G.hn project [161] with the goal of developing a next generation of unified home data network transceiver capable of operating over a variety of wired media, including power lines, with bit-rates up to 1 Gbps. In 2010, IEEE published the IEEE 1901 Standard, which is capable of supporting a transmission rate up to 500 Mbps. Finally, in 2015, the G.hn Standard was launched [55].

Currently, PLC has been gaining significant attraction on the global market. Companies worldwide are developing and commercializing PLC technologies and launching innovative products. For instance, Texas Instruments [162] and Atmel [163] manufacture NB-PLC chipsets for smart things with support for G3-PLC, IEEE 1901.2 and PRIME standards; Maxim Integrated [164] commercializes NB-PLC chipsets compatible with IEEE 1901.2, ITU-T G.hnem, G3-PLC and PRIME standards; Qualcomm [165] manufactures BPLC chipsets for smart-things, multimedia and in-vehicle applications based on HomePlug standards and IEEE 1901; MegaChips [166] manufactures PLC chipsets for smart things applications fully compliant with HD-PLC; Panasonic [167] manufactures BPLC chipset for multimedia based on HD-PLC; Marvell [168] manufactures chipsets compatible with ITU-T G.hn for home broadband network connectivity.

The aforementioned PLC standards present physical and link layers parameters and characteristics that allow interconnection and coexistence with other data communication systems (PLC or not), besides ensuring the correct operation of the data communication system and usage of all available resources. Tables 2 and 3 list some of the main NB and BPLC standards, respectively, highlighting their MAC methods and their main applications. Note that all NB-PLC standards use CSMA/CA in which only active users contend for the communication medium. CSMA/CA is suitable for reducing energy consumption and improving resource sharing in applications such as smart things (i.e., smart grid, smart meter and smart home) and in-vehicle data networks [35, 131]. On the other hand, there are BPLC standards that also consider the use of TDMA [169], in general, for multimedia and real time applications [42, 107]. In fact, the predictable round-trip time of the TDMA is desirable for applications with strict QoS requirements, as mentioned earlier.

Table 2: NB-PLC standards.

Standard	**MAC Method**	**Main applications**
PRIME [156]	CSMA/CA	smart things
G3-PLC [170]	CSMA/CA	smart things, in-vehicular
IEEE 1901.2 [54]	CSMA/CA	smart things, in-vehicular
ITU-T G.hnem [56]	CSMA/CA	smart things, in-vehicular

Table 3: BPLC standards.

Standard	**MAC Method**	**Main applications**
HomePlug 1.0 [52]	CSMA/CA	home area networks
HomePlug AV [149]	CSMA/CA, TDMA	multimedia
HomePlug AV2 [171]	CSMA/CA, TDMA	multimedia
HomePlug GP [172]	CSMA/CA	smart things, in-vehicular, multimedia
IEEE 1901 [53]	CSMA/CA[1], TDMA	smart things, in-vehicular, multimedia
HD-PLC [173]	CSMA/CA, TDMA	smart home
ITU-T G.hn [55]	CSMA/CA, TDMA	smart things in-vehicular
ITU-T G.hn-MIMO [174]	CSMA/CA, TDMA	home networks

2.3 PLC MAC PROTOCOLS FOR SMART THINGS

Internet of Things (IoT) has been attracting significant research attention due to its wide applicability to information technology and industry [177]. The basic idea of this concept is the interconnection of a variety of objects (e.g., electric and electronic devices) [178], which create scenarios of pervasive technology, such as smart cities, smart homes, smart grid, among other smart things. In this context, PLC systems are attractive for providing the interconnection of electric and electronic devices, because they are usually already plugged into the electric power grids through outlets. In the following subsections, the MAC sublayer is discussed from the perspective of "smart things".

[1] Recently, Vlachou et. al [175, 176] analyzed the IEEE 1901 Standard and proposed modifications to enhance its CSMA/CA performance when compared to its default configuration.

2.3.1 Smart Grid

Historically, the first PLC applications were related to load management, electricity meter reading and telephonic communications [33, 66]. Nowadays, companies are investing in the concept of smart grid as the main PLC application. This investment is due to environmental concerns such as rising fuel costs and the energy crisis, since smart grid can avoid energy waste by providing full visibility and pervasive control of utility companies over their assets and services [179].

Smart grid are modern electric power systems that improve the efficiency and resilience of energy generation, transmission, delivery and consumption in terms of security, reliability and flexibility [180, 181]. These modern grids help customers control their power consumption and, consequently, reduce energy demand and usage. Moreover, they enable the integration of renewable energy sources into the grid. Therefore, smart grid advantages are beyond financial achievements and also positively impact environmental issues [182]. In the literature, there are interesting surveys regarding smart grid challenges, motivations and open issues [183–185]. Thus, the present section focuses on discussing PLC MAC protocols in the context of smart grid applications. Figure 6 shows the smart grid interconnecting smart applications and renewable energy sources.

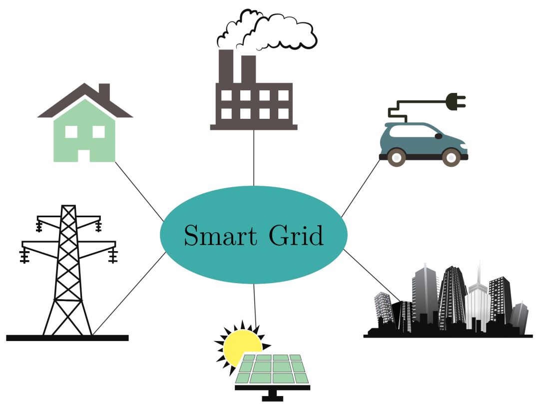


Figure 6: Smart Grid interconnecting industry, home, electric cars and renewable energy sources.

Overall, smart grid heavily rely on the use of pervasive telecommunication infrastructure. In this sense, [186] compared several possible data communication systems and showed that PLC is an attractive data communication technology for several smart grid applications. In summary, the use of preexistent infrastructure, which reduce installation costs, is one of the main motivations for using a PLC system in smart grid deployments. Moreover, PLC systems are independent of third parties (e.g., Internet or cellular service providers) [187] and can work as distributed sensing systems. Furthermore, [179] quoted PLC as one of the fastest technologies for data communication purposes at low cost and least impact on the environment, when compared to other technologies. These PLC advantages are favorable to the development of various smart grid applications. In this context, [188] and [148] describe smart grid applications, such as remote power grid configuration, dynamic pricing, advanced metering and load control, using PLC.

In this regard, it is important to discuss suitable MAC protocols in order to efficiently assist smart grid applications based on PLC systems [127, 128]. In the literature, there are authors who proposed the use of contention-free protocols instead of contention-based protocols in NB scenarios [95]. They showed that the latter lose more performance than the former when the number of active data network users increases. Regarding BB scenarios, it is also possible to use contention-free protocols to reduce performance deterioration in saturated data networks. In this case, TDMA time-slots can be used for more than one user without collision by considering a tree topology and correctly selecting nodes that are able to share time-slots [36]. However, the drawback for using tree topology is that network nodes need to exchange control messages in order to know its descendants and ancestors. Furthermore, each new node connected to the tree needs to repeat the process of exchanging control messages.

In spite of the aforementioned statements, [35] considered that contention-based protocols are more efficient in smart grid applications than contention-free protocols because the former yields lower latency than the latter. Moreover, in [122], the authors showed that it is possible to improve CSMA/CA, a well-known contention-based protocol, performance in large scale networks in terms of throughput, delay and packet loss rate, motivating the use of contention-based protocols in BPLC systems. Furthermore, [35, 98] proposed analytical models to analyze the CSMA/CA performance in NB-PLC systems. In fact, the majority of PLC standards for smart grid (e.g., HomePlug GreenPhy (Homeplug GP) [172] and IEEE 1901 [53]) uses CSMA/CA as their main MAC method. On the other hand, [37] proposed data network designs for centralized BPLC systems based on orthogonal frequency division multiple access-TDMA (OFDMA-TDMA) and for distributed BPLC systems based on OFDMA-CSMA. However, they did not present comparative results of protocols based on these methods.

Hybrid MAC protocols that use both TDMA and CSMA/CA were described in [100, 141]. More specifically, in [141], the use of an adaptive layer switching mechanism was proposed, allowing the changing of the MAC method in the runtime depending on the network utilization. When the network utilization is low, TDMA-based protocols are not recommended, since inactive users' time-slots will remain idle. In this case, the proposed protocol switches to CSMA/CA mode in which only active users contend for the channel access. Otherwise, when the network utilization is high, contention-based protocols lose performance due to an increase in the collision rate. In this case, the proposed protocol switches to TDMA mode. In spite of good results, this protocol requires the use of a master coordinator that is capable of switching the operational modes. Moreover, there is a switching time that needs to be considered in order to use the proposed protocol.

In [100], a hybrid protocol was proposed to divide a frame into a contention-free period and a contention-based period. During contention-free period, each user has a time-slot to access the channel. In the contention-based period, the authors consider a priority-based CSMA/CA protocol in which the highest priority belongs to control messages. Users that access the channel during contention-free period may contend for a new access during contention-based period again. Results show throughput improvement as well as delay and collisions reduction when compared to protocols based solely on TDMA or CSMA/CA. Note that, in [100], TDMA and CSMA/CA periods will always exist during every frame thus eliminating the required switching time associated with the approach in [141], but it faces the TDMA disadvantages when the network use is low, and the CSMA/CA disadvantages when the network use is high.

In general, it is common to find, in the literature, proposals for adjusting CSMA/CA CW or backoff period to improve performance of smart grid applications. The authors usually propose algorithms to calculate the CW optimal size adaptively, according to the number of active data network users [124–126]. In this sense, [27] introduced an adaptive algorithm to determine backoff periods, also considering the number of active users, which has a good synergy with adaptive CW adjustments. However, numerical results from another work [123] showed that the use of polynomial and of exponential distributions to determine the backoff period reduce collision probability when compared to the use of adaptive algorithms. In this context, [34] compared different backoff algorithms in terms of key performance parameters, such as goodput, fairness and collisions. In [121], a channel prediction approach was proposed in order to reduce collisions and packet losses when compared to traditional CSMA collision avoidance method in BPLC systems. Furthermore, the authors highlight that it is rare to find, in the literature, approaches that consider statistical regularity in the scope of the MAC sublayer of BPLC systems.

There are also authors who advocate the modification and adaptation of wireless standards for a PLC scenario [97]. Essentially, they outlined the adaptation of the IEEE 802.15.4 Standard [189] (NB wireless sensor data networks) to NB-PLC systems, aiming at offering low energy consumption in a smart city. This adaptation included modifications in the IEEE 802.15.4 MAC sublayer specifications by incrementing the waiting time duration for acknowledgement responses in the adopted contention-based protocol (based on CSMA/CA). Despite showing interesting results, this adaptation also required hardware modifications, which could be avoided by considering the use of a default PLC standard.

2.3.2 Smart Meters

Historically, automatic meter reading (AMR) and advanced metering infrastructure (AMI) are recognized as critical steps in the smart grid world [190]. A smart meter is an electrical meter capable of recording information about electric power and energy consumption. Additionally, it is also capable of remotely reporting metering information back to the utility for controlling, monitoring and billing functionalities (see Figure 7). However, these monitoring functionalities can also create privacy problems, which are matters of concern in recent studies about the smart meter application [191, 192]. In fact, through power consumption information, it is possible to determine working hours, periods in which a family is not at home, among others valuable information for thieves.

In this regard, the development of new MAC protocols for smart meter applications that consider privacy issues is an important research topic. In this sense, [191] highlighted confidentiality, integrity, authenticity, non-repudiation and auditability as the main security requirements for privacy-preserving protocols. Moreover, in order to ensure billing privacy, [192] recommended the use of a trustful third party or the customer itself for calculating the bill and ensure its correctness via a trusted computer or via cryptography. The main drawbacks of these approaches are that the use of a third party increases the infrastructure complexity, the use of a trusted computer requires additional hardware and the use of cryptography may increase the smart meter complexity.

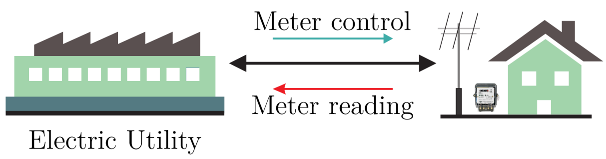


Figure 7: Smart meter basic operations

In the literature, it is possible to find several works that modify preexistent PLC standards and protocols in order to improve meter reading performance. For instance, [48] verified the impact of the digital modulation scheme on the performance of the PRIME Standard [156] in a cross-layer approach, which involved physical and link layers. The PRIME Standard was designed for smart meter applications based on NB-PLC systems and it uses contention-based protocols, related to CSMA/CA. This work concluded that low order digital modulation constellations improve performance at the physical layer, but the digital modulation scheme does not influence the collision rate of CSMA/CA. Thus, the authors proposed an increment of CW size in order to reduce the number of collisions. However, this work did not show any results attained with CW size variation, and, thus, more research remains to be done in this area. It is important to emphasize that an increment in the CW size reduces collisions but leads to an increment in the channel access delay [81]. Nevertheless, different from QoS-oriented or real-time applications, which have strict delay requirements, smart meter applications are less sensitive to CW adjustment approaches.

The use of contention-free MAC protocols, such as polling, is also a common approach for AMR applications. According to [101], it is motivated by the high throughput of polling protocols for meter reading purposes, when compared to contention-based protocols. Nevertheless, this work pointed out that the data collection delay for polling protocol is higher than that for contention-based protocols. In other words, there is a trade-off between data collection delay and throughput and this work focused on balancing these metrics by using a hybrid protocol. Moreover, [102] proposed a hybrid protocol for AMR applications, given that polling protocols are not capable of automatically managing associations with new meters to the PLC system. Furthermore, the authors analyzed different methods to combine the contention-free with the contention-based protocol, which is a matter of concern when hybrid MAC protocols are considered. In the literature, it is common to find hybrid MAC protocols that divide the frame duration between a contention-based period and a contention-free period. This frame-division approach requires synchronization among all network nodes, which, consequently, reduces collisions. However, in [102], the authors used a different approach in which both types of protocol are superimposed so as to eliminate synchronization issues at the cost of an increase in the collision rate.

2.3.3 Smart Homes

Smart homes attracted researchers' attention with the advent of IoT. For instance, [193] addressed smart home and home automation concepts, focusing on providing connectivity of devices in a home (home area network - (HAN)) in order to establish continuous control over such devices and appliances as surveillance cameras, lights, thermostats, among others (see Figure 8). In this context, the use of PLC systems is justified by the poor propagation quality of wireless data networks, under certain conditions, which brings wired connections back into research focus [118]. Additionally, [117] analyzed in-home PLC and wireless systems and the overall results showed that, for the studied cases, the former outperforms the latter for reliable connection service and throughput.

Figure 8: Smart home functionalities.

BPLC standards (e.g., HomePlug 1.0, HomePlug AV, ITU-T G.hn and IEEE 1901) have been facilitating the development of household applications based on PLC systems, such as, multimedia, data networking and security protection devices, which can be connected and controlled conveniently by a general remote-control device [194]. In this sense, [38] introduced a frame structure, aiming to provide integration of various kinds of home services and to optimize the use of the PLC system. The use of the proposed MAC frame leads to a better framing efficiency when compared to the use of a HomePlug 1.0 MAC frame. The main difference between these MAC frames is that the HomePlug 1.0 Standard specifies a peer to peer communication protocol over a PLC system, while the proposed MAC frame is specifically built for smart home applications, addressing their specific QoS requirements. Other than integration of home devices, energy consumption is also a matter of concern related to the in-home scenario. More specifically, the development of new MAC protocols for in-home PLC systems focus on energy management and consumption as important research issues, since home energy usage tends to increase as the variety and number of home electronic devices increase. In [195], the authors proposed a smart home technology called Home Energy Management System (HEMS) focused on two home energy scenarios: consumption (e.g., lights) and generation (e.g., solar energy). HEMS monitors both energy consumption and generation to minimize their cost. A drawback of this proposal is the lack of justification for the use of MAC specifications from the IEEE 802.15.4, which, originally, focus on low-rate wireless networks. Moreover, the authors did not present results related to the use of the proposed technology.

The advent of smart homes and smart devices leads to heterogenous QoS requirements for MAC throughput, channel access delay and priority-based channel access, to name a few. Thus, [83] evaluated MAC efficiency and medium access delay performance of in-home BPLC systems based on the HomePlug MAC. They considered saturated data networks with prioritized traffic streams and concluded that the HomePlug MAC guarantees QoS requirements in such scenarios. In spite of this conclusion, there are numerical analyses about HomePlug 1.0 performance [45,46] that show that high priority users have high collision probability in a saturated data network of an in-home BPLC system, since their CWs are small. In fact, collision is a common problem in contention-based protocols such as the ones based on CSMA/CA. As an alternative to mitigate this problem, the use of CSMA/CA in a data communication system based on OFDMA scheme can reduce collision rate and, as a consequence, improve system throughput [44, 99, 119]. In OFDMA-CSMA/CA, a channel is subdivided in a set of subchannels. Each user receives subchannel state information together with data message receptions. Then, each user chooses the best idle subchannel to start its backoff period. Note that the collision rate reduction occurs because the contention period is distributed among different subchannels, reducing the number of users contending for a single subchannel.

Contention-free and hybrid protocols are also alternatives to deal with the disadvantages of contention-based protocols [137]. For instance, [103] proposed a contention-free protocol to solve resource allocation problems of TDMA-based in-home MAC protocols. In general, in TDMA-based MAC protocols, time-slots of inactive users are not removed from MAC frames, which represents a waste of network resources. In order to mitigate this problem, the authors calculated the optimal duration of time-slots based on data network dynamics. Basically, time-slots are dynamically distributed to each user by a central coordinator based on QoS information. This approach may improve resource sharing fairness in TDMA-based PLC MAC protocols, because this dynamic sharing of network resource allows the elimination of idle time-slots by allocating network resources only for active users. Lastly, in [118], although the authors focused on the contention-based part of the proposed protocol, they discussed a hybrid protocol to improve throughput of in-home BPLC systems using a central coordinator that determines whether or not a given node will contend for the channel resource. However, the authors recognized that control messages overhead is a common problem associated with the use of central coordinator nodes, which may limit throughput improvement. The mitigation of this problem is an open research issue to improve the proposed protocol.

2.4 PLC MAC PROTOCOLS FOR MULTIMEDIA

Multimedia refers to an interactive scenario among users as well as a combination of electronically delivered media (e.g., video, audio, text, images). This interactive scenario has the challenge of ensuring QoS, quality of experience and quality of perception, which are surveyed in [196]. Additionally, in [197], there is a survey about forward error correction techniques for low delay multimedia applications, which may also improve users' experience. In this context, the PLC advantages associated with multimedia applications has been attracting research attention. A comparative performance study between wireless communication and PLC systems in multimedia scenario concluded that, while the former offers convenience and mobility, it suffers from overall stability problems common to wireless channels, which share spectrum with other interfering applications such as microwave ovens. The latter, in contrast, has shown more stability, while also offering higher transmission rates [198].

The launch of the HomePlug AV Standard [149, 199] further motivated the use of multimedia applications based on PLC systems. The QoS requirements of these applications using this standard were presented in [145]. Latency and jitter were shown to be important parameters, since multimedia includes real time applications (e.g., video streaming). In this regard, a MAC scheme aiming at reducing jitter and latency, and, as a consequence, improving multimedia application performance appeared in [111]. Despite the good results showed by the proposed protocol, it requires an augment of six octets in the control message size in order implement the needed priority scheme. Moreover, the authors did not discuss the QoS deterioration that may occur when new users connect to the data network even when a priority scheme is considered. In this case, it is important to avoid excessive augmentation of latency and of jitter. In this sense, [87] offered a protocol that is activated when these QoS parameters start deteriorating. Essentially, [87] defined jitter and latency thresholds for different multimedia applications. When these parameters of a given user reach the threshold, this user sends an alarm message to the data network central coordinator. Then, the central coordinator analyzes all users QoS conditions and transfer resources from users in a “good” condition to users in a “bad” condition to achieve fairness in data network resource allocation. Results showed improvements when compared to the CSMA/CA implemented in the HomePlug AV Standard. However, these results require the use of a central coordinator, which limits the protocol applications. Furthermore, the use of proposed protocol may be challenging in terms of control message overhead related to the alarm messages.

In the context of improving CSMA/CA, [114, 115, 126] proposed the use of this method together with an OFDMA scheme to make possible the full utilization of the frequency spectrum of a PLC channel. The main challenge of this proposal is to overcome the necessity of a master node to coordinate the allocation of sub-carriers. In this regard, the authors proposed schemes that perform this coordination in a distributed manner, without the need of a central coordinator. Results showed throughput improvements when compared to CSMA/CA together with OFDM scheme, such as the one in the HomePlug standards. Moreover, [114] identified a trade-off between throughput and delay in the CSMA/CA of the IEEE 1901 Standard. In case throughput falls below a recommended threshold, a reconfiguration of data network parameters in order to balance this trade-off is required.

In multimedia scenarios, it is common to find proposals to adjust CW or backoff period of CSMA/CA from BPLC standards. For instance, [51, 116] showed that the efficiency of contention scheme of the HomePlug 1.0 Standard at the link layer level tends to deteriorate drastically in saturated data networks. In order to overcome this problem, [51, 116] suggested modifications in the CW of CSMA/CA assuming that all data network nodes know exactly the number of active nodes contending for channel access. In [50, 152], a dynamic CW size adjustment was proposed by considering the number of successful transmissions and the number of idle slots during signaling period. Results showed performance improvements in relation to the CSMA/CA of the HomePlug 1.0 Standard even in saturated data networks without the need to know the number of contending nodes.

Nevertheless, according to [112], aforementioned proposals focus only on high priority users without any concern about the low priority ones. Accordingly, a cross-layer protocol involving the MAC sublayer and the physical layer was introduced in [112]. This protocol exploits the cyclostationarity property of PLC channel. Channel access is granted to multimedia applications when signal-to-noise ratio (SNR) is high and to data transmission when SNR is low. Results showed that the mean throughput of low priority users can improve up to 300% when using the cross-layer protocol (opportunistic CSMA/CA) in comparison to CSMA/CA. This protocol is interesting not only for multimedia, but for any PLC application that uses priority-based CSMA protocols. A drawback of this work, however, is that the authors assumed that the SNR only varies synchronously, decreasing or increasing its values in all sub carriers. Thus, they did not show results for more complicated models in which this assumption does not apply.

Improvements to HomePlug 1.0 with regard to data transmissions other than multimedia data were discussed in [113]. It involves choosing which type of traffic will receive channel access: multimedia traffic or data traffic. Results showed delay reduction and throughput improvement in multimedia traffic and a frame drop reduction in data traffic when compared to HomePlug 1.0 without the proposed enhancements. However, the authors did not compare their results with the use of HomePlug AV or HomePlug AV2, which could be interesting to comprise a wider range of multimedia applications such as high-definition television (HDTV) and voice over internet protocol (VoIP).

In this regard, [49] analyzed CSMA/CA backoff period and proposed a simplified mathematical model considering saturated data networks for the HomePlug AV Standard. The authors highlight resource sharing fairness and starvation as challenges to be solved at the link layer level. The proposed mathematical model can be used to detect starvation resulting from the priority resolution scheme, which precedes CW. Furthermore, the authors pointed out that a full demonstration of the conditions in which the deferral counter of the CSMA/CA improves the performance of the network is an open research issue. Later, as an alternative to overcome the starvation problem, in [82], it was proposed the use top priority messages only for signaling purposes. However, in spite of the simplicity of the proposed solution, it was not well explored until the concluding remarks. Furthermore, the authors highlighted the vulnerability of the analyzed PLC system to denial-of-service attacks, although this subject was also little explored.

Note that all aforementioned protocols are based on CSMA/CA. As an alternative, [106] directed attention to performance comparison among TDMA, ALOHA and CSMA/CD considering multimedia applications in BPLC systems. Results showed that CSMA/CD presented the best results in terms of delay, throughput and packet loss rate. In [139], the authors also show good results related to the use of CSMA/CD. However, collision detection requires a full duplex communication, because users that perform data communication need to sense the channel until the transmission ends. Thus, contention-based protocols that use CSMA/CD may adopt a multi-band OFDM (MOFDM) scheme with two sub-bands of frequency [138]. One of these sub-bands can be used for detecting collisions while the other for transmitting data.

Hybrid protocols are also interesting to broadband multimedia applications. In this context, some works suggest the use of virtual slot multiple access (VSMA), which hybridize TDMA and CSMA/CA [142,143]. The former is used in real time applications and the latter is used in best effort applications. Additionally, VSMA considers the existence of virtual slots. A data network node that is using CSMA/CA needs to check the virtual slot before starting to contend for channel access. If this virtual slot is idle, this node can access the channel during this slot and transmit data skipping the CW. The result is reduced delay and improved throughput of VSMA in comparison to CSMA/CA or TDMA. On the other hand, the use of VSMA demands the implementation of virtual slots, which adds complexity to the MAC sublayer.

Furthermore, [144] focused on a hybrid protocol based on the use of both CSMA/CA and TDMA in a multimedia scenario. More specifically, this work proposed a real time error handling technique that offers a trade-off between data communication reliability and system throughput. In this regard, the authors presented an adapted hybrid protocol in which the TDMA is capable of allowing a parent device to control bandwidth in real time according to traffic volume. In the CSMA/CA period, however, bandwidth is not guaranteed. A drawback of this work is the control message overhead during the TDMA period in which the parent device needs to notify each device of a bandwidth schedule. Moreover, synchronization issues may be a challenge for the proposed solution.

There are also proposals for contention-free protocols for multimedia applications, in BPLC systems. In general, these protocols are built around a central coordinator node [105]. For instance, a protocol based on the TDMA scheme in which the coordinator node chooses a set of nodes that can share the same time-slot was addressed in [107]. Results showed throughput improvement and delay reduction compared to traditional TDMA. Additionally, [104] analyzed the protocol based on TDMA proposed in the OPERA Standard [200]. In this protocol, the coordinator node sends a token to the node that will access the channel during the next time-slot. Results showed that repeaters improve performance in terms of reliability, but it has a negative impact on end-to-end delay. Furthermore, [200] also discouraged the use of this protocol, since channel access delay increases as the number of users increase.

Note that there were improvements attained in aforementioned centralized protocols based on TDMA. However, control messages overhead is a common issue in scenarios in which there is a central coordinator node and, also, such protocols tends to suffer higher delays than distributed ones [57]. As an alternative, several researches supported the use of distributed protocols based on the ALOHA protocol [109, 133–136]. Nevertheless, in this case, it is important to consider collision avoidance strategies, because collision is one of the major ALOHA protocol drawbacks [201].

2.5 PLC MAC PROTOCOLS FOR IN-VEHICLE DATA COMMUNICATION

In-vehicle PLC refers to communication applications related to any means of transportation, such as aircrafts, ships, cars and trains. Nowadays, vehicles have many electrical control units (ECUs) for the safety (e.g., antilock-braking systems) and comfort (e.g., adaptive cruise control and multimedia systems) of its occupants [202]. Thus, it is desirable to implement an in-vehicle data network in order to control vehicular electronics. Recent architectures, achievements and challenges in the scope of in-vehicular data networks are surveyed in [203, 204]. It is important to emphasize that the main requirements of these networks are: security, to prevent the vehicle from being hacked; reliability, to avoid command failures and provide real-time responses to deal with critical system's demands [40].

With the advent of fully electric vehicles, the following advantages associated with PLC systems emerged: it enables exploiting the existing in-vehicle challenges for data communication purposes, reduces vehicle weight by decrementing the amount of dedicated cables for data communications, reduces manufacturing and operational costs associated with cable installations, and increase reliability [205]. Moreover, the weight reduction improves vehicle performance and increases its efficiency in terms of fuel consumption. Applications that could be covered by PLC system in these scenarios, include data transfer among sensors and actuators, traction control, automated battery charging with metering and billing, among others [206].

There are authors who defend the use of contention-based protocols for PLC in-vehicle applications. For instance, [40] proposed a contention-based protocol, considering an OFDMA scheme in which each data network node contends for a random subchannel. In summary, this protocol may reduce channel access delay, collision rate and, as a consequence, improve reliability of an in-vehicular NB-PLC system. It is interesting to highlight that, as the allocation of the subchannel is granted through a contention period, a coordinator node to perform this allocation is not needed. Nevertheless, the authors keep a practical implementation of the proposed protocol as a challenging open research issue. Moreover, [131] addressed a contention-based protocol aiming at providing a reliable, compact and energy efficient in-vehicle data network. This work considered the use of the standard HomePlug Green PHY for in-vehicle BPLC, which showed good results for non-critical applications. However, results related to critical applications are pointed out as an open research issue. Furthermore, [129, 130] introduced a contention-based protocol for minimizing collisions in a BPLC in-car application. The authors outlined a modified CSMA/CA that uses an arbitration procedure for detecting and resolving contention. This work showed good results in terms of collision probability reduction, but the proposed procedure generates a data packet overhead.

Despite the interesting results related to contention-based protocols, there are arguments against their use in real-time applications for in-vehicle data communication purposes. For instance, [42, 108] discarded the use of CSMA because of collision rate, control messages overhead and starvation probability in an in-car BPLC system. Thus, the authors proposed a priority-based contention-free protocol using TDMA and the priority scheme of HomePlug AV and of IEEE 1901. This protocol also focuses on improving energy efficiency by putting non-active nodes in standby mode. In spite of the good results, the authors did not consider time-slots with a variable size, which could improve even more the resource sharing fairness of the proposed contention-free protocol. Regarding this subject, it is recommended the reading of [207], which presents an interesting purpose for time-slots allocation that could be adapted to in-vehicle applications.

Alternatively, [41] proposed the use of a hybrid protocol, called Priority-based Medium Access, which combines the flexibility of CSMA/CA with the reduced overheads of TDMA, depending on the number of active nodes in an in-car BPLC system. As a comparative analysis among contention-based, contention-free and hybrid protocols, the numerical results are favorable to the use of hybrid protocols. It was expected, since these protocols trade versatility for simplicity. In other words, hybrid protocols are able to deal with a wider range of data communication challenges, since it offers advantages from both contention-free and contention-based protocols.

2.6 FUTURE TRENDS

This section aims to present open research topics that could motivate the emergence of new proposals toward the improvement of the data communication over PLC systems within the scope of the MAC sublayer. In this regard, some application-oriented insights and open problems are identified, which could be useful information for the PLC community. Then, PLC and wireless networks similarities are highlighted in order to find interesting research topics yet little explored in the PLC scenario. Further, several open research issues and appealing suggestions for reliability improvement at the link layer level of PLC systems are presented. Lastly, but not the least, promising resource sharing approaches that could be adapted for PLC systems are presented.

2.6.1 Application-Oriented Insights and Open Issues

During the analysis of the main PLC applications, interesting open research issues that could be considered in future works were identified. For instance, regarding the smart meter application, the development of MAC protocols considering potential privacy problems [191, 192] is an important research topic in order to avoid the misuse of the meter reading information. Regarding the smart home application, the development of MAC protocols considering energy consumption and management issues is an appealing approach, since the number of electronic devices in an in-home scenario tends to increase [195]. Regarding the multimedia application, the vulnerability of PLC systems to denial-of-service attacks is a relevant issue yet little explored [82]. Regarding the in-vehicle application, the use of the OFDMA scheme in order to reduce collisions and channel access delay is an interesting subject. In [40], the authors propose a MAC protocol to address this topic, but a practical implementation of the proposed protocol is still an available task. Moreover, the development of energy efficient MAC protocols for critical in-vehicle applications is also an open research issue [131]. In this context, the use of contention-free MAC protocols with a variable time-slot size [207] for optimizing the use of the network resources is a promising topic yet little explored for in-vehicle critical applications.

2.6.2 PLC and Wireless Networks Similarities

PLC data networks are similar to wireless networks in many aspects, such as their broadcast transmission propagation and their use of time-varying frequency selective channels [208]. Thus, many characteristics of PLC Standards, methods and protocols are closely related to the corresponding wireless ones. For instance, it is well known that the CSMA/CA of the IEEE 1901 and the HomePlug AV Standards are quite similar to the CSMA/CA of the IEEE 802.11 Standard for wireless data networks, apart from some modifications in the exponential backoff algorithm and provisions for traffic prioritization. However, there are still several advances regarding the MAC sublayer related to wireless communications that can be very appealing for advancing the MAC sublayer of PLC systems in order to address the diverse demands and requirements related to Smart Things, IoT, multimedia, in-vehicle and, more recently, the advent of the Industry 4.0. In this regard, it is important to emphasize that cooperative communication at the link layer, network coding, hybrid automatic repeat request (ARQ) [209–211] and non-orthogonal multiple access (NOMA) schemes [212, 213] are promising research topics for PLC systems. Furthermore, slicing and software-defined MAC sublayer investigations may offer additional improvement to ensure flexibility and adaptability of PLC system at the link layer level. Therefore, the further investigation of the aforementioned topics is a new endeavor for introducing new generations of PLC systems.

2.6.3 Reliability Improvement

In order to improve data communication reliability at the link layer level of PLC systems, relayed transmissions are an interesting approach that may exploit communication diversity [214]. In this regard, cooperative communication at the link layer (e.g., cooperative MAC protocols) uses neighbor nodes as relays to intermediate data transmissions or retransmissions between a source node and a destination node [198]. For instance, [85] showed that a cooperative MAC protocol is capable of reducing packet loss rate up to 43% when compared to a PLC system without cooperation in the studied scenario. In addition, PLC MAC protocols are easier to implement than cooperative protocols at the physical layer, since the former do not require system modifications in terms of hardware. Therefore, the development of new cooperative PLC MAC protocols is an interesting issue in order to introduce improvements in the current standards and preserve their physical layer legacy, which is more difficult to modify. Nevertheless, most of the works about cooperative communication in PLC systems are mainly focused on the physical layer [215].

Other than cooperative communication, network coding can, also, improve data communication over PLC systems. In fact, network coding can optimize the data communication flow by coding multiple data messages into a single data message, which is broadcasted and decoded by its receivers [216]. The use of network coding can reduce data communication overhead and improve system performance [86] at the link layer and this is an approach that remains to be more deeply exploited for PLC systems.

Another approach little explored in the context of PLC systems is the one based on the hybrid ARQ technique, which can enhance data communication reliability by correcting corrupted data packets. This kind of packet correction technique is performed at the physical layer by using, for instance, turbo or polar codes, after considering negative acknowledgement (NACK) messages from an ARQ technique. In such context, corrupted data packets could be stored at their destination node reception buffer and combined in order to find and, then, correct their erroneous bits [211]. In the literature, it is common to find hybrid ARQ techniques associated with chase combining [217] or incremental redundancy [218] techniques. The chase combining technique requires retransmissions of the same (complete) packet by the sender, on every NACK from receiver, until either the packet is accepted or a threshold number of retransmissions has been made. Each new packet is combined with the previous ones to get a better version of the earlier. Otherwise, the incremental redundancy technique requires the retransmission of redundancy symbols each time a NACK is received. Thus, different code rates can be obtained with each retransmission by varying the number of parity bits. Regarding both techniques, in [219] was shown that, generally, incremental redundancy provides a better throughput than chase combining. However, when the signal to noise ratio varies widely, the latter can outperform the former in wireless communication systems. It is important to point out that hybrid ARQ is little explored in PLC systems although it yields interesting results in wireless systems. Therefore, its investigation defines appealing research endeavors for improving the performance of PLC systems at the link and physical layer levels.

Another kind of hybrid ARQ may arise by correcting corrupted packets at link layer, instead of physical layer, by using simple techniques in order to avoid requirements for changes in the systems in which these techniques could be used. In this sense, it could be interesting to use a cooperative MAC protocol together with the packet correction technique, because the diversity provided by the former is favorable to the error detection and correction performed by the latter.

As an alternative to improve reliability of data communication, hybrid PLC-wireless scenarios can improve system diversity [28, 74–77, 220]. In such scenarios, data communication is performed through PLC and wireless channels working in parallel. More specifically, after any transmission, the reception buffer of destination nodes has at least two copies of the same data packet: one received through a PLC interface and another received through a wireless interface. In this sense, the use of chase combining techniques, which use copies of the same packet for detecting erroneous bits, might be a promising approach yet little explored in such scenario. This approach can highly improve system performance and robustness due to the exploration of the diversity offered by the hybrid channels. The design of MAC methods and protocols addressing both hybrid combinations of PLC and wireless channels (i.e. serial and parallel combination) constitutes a challenging issue to be pursued.

Regarding Smart Things scenarios, there is a variety of devices (e.g., meters, poles, equipment and sensors) with heterogeneous data communication needs to be fulfilled by the available telecommunication infrastructure. In this context, resource slicing could be a viable approach for improving the network resource utilization in PLC systems. According to the literature, slicing is defined as a subset of network resources allocated to a coordinator node (virtual operator or service provider) [221]. These resources can be distributed, by the coordinator node, to a subgroup of end users. Note that, in a single network, resources can be divided among different slices independent from each other. For the aforementioned applications, slices could be used to guarantee specific quality of service (QoS) requirements to a specific subset of devices. In an in-vehicular network, for example, real-time applications could receive a resource slice different from ergonomic applications. In this case, each slice could receive adequate resource, respecting their specific characteristics, in a single network. Although promising, resource slicing has not been investigated in PLC systems context. Thus, it is an interesting open research topic for improving the performance of PLC systems at the link layer level.

2.6.4 Resource Sharing Improvement

In order to optimize the use of the available resources in a data communication system, the heterogeneity of the aforementioned applications has also inspired relevant studies on packet size optimization [222]. The use of larger packet sizes may trade a reduced payload-to-overhead ratio for an augmentation of the packet error rate and for a higher transmission power level assignment, which decreases the energy efficiency of the PLC system. On the other hand, the use of small packets trades reduced packet error rate and improved energy efficiency of the PLC system for a high payload-to-overhead ratio. These trade-offs, although studied for wireless sensor networks, are little explored in PLC systems related to Smart Things and IoT applications. Innovative PLC MAC protocols could be developed in order to modify the packet size adaptively, by using bigger packets when the channel SNR is high and fragmenting the data among smaller packets when the channel SNR is low. This approach can also improve the reliability of PLC systems. Overall, this kind of research efforts may result in precise data packet size specifications for fulfilling characteristics of very distinct demands of each application discussed in the present chapter.

Additionally, the novel approach used in medium access related to 5G [223, 224] holds significant promise for the design of new generations of PLC systems. For instance, recent investigations on 5G have focused on NOMA schemes [212, 213], which is an appealing approach to improve wireless system throughput, handle access collisions and allow massive connectivity demands inherent to Smart Things applications.

Orthogonal multiple access (OMA) schemes [225], such as TDMA and OFDMA, serve a single user in each orthogonal resource block. As an alternative to improve communication in scenarios with massive connectivity, such as 5G networks or smart grid scenarios, NOMA schemes can serve multiple users in the same resource block without dividing the bandwidth [226]. As a consequence, NOMA schemes are able to provide higher system throughput, better fairness of resource sharing and reduced electromagnetic compatibility issues in PLC systems [227]. A cooperative MAC protocol in which source and relay nodes could retransmit data together in the same time-slot, by considering a NOMA scheme, is an idea yet unexplored in PLC systems. In addition, further investigation of NOMA schemes for both narrowband and broadband applications is still an open research issue in the PLC context.

Finally, but not the least, the significant increase of devices demanding data communication motivate a revisiting of other medium access techniques based on multi-user concepts, such as code division multiple access, multicarrier-code division multiple access, and the multichirp-code division multiple access [228], because they can increase the fairness by maximizing the use of limited channel resources among connected devices. Moreover, it would be interesting to focus, in the MAC perspective, on recent findings related to the energy efficiency and the delay reduction from wake-up radio techniques of wireless sensor networks [229] and the efficient utilization of the available spectrum based on the cognitive radio concepts [230], because the high increase of devices demanding connectivity means that the energy consumption and the network resource sharing must be optimized. Furthermore, the correct investigation of software-defined radio concepts [231], in the MAC perspective, may be very appealing research topic to allow PLC systems to cognitively operate, at the link layer level, in a time-varying environment, which characterizes electric power grids, with dynamic resource demands from users. Overall, new efforts related to the open research topics may offer additional improvements in the performance of PLC systems in terms of the MAC sublayer. It is important to improve flexibility and real-time adaptability of the MAC sublayer in order to enable PLC systems to deal with the dynamics of environment and applications.

2.7 SUMMARY

The main contributions of the present chapter are summarized as follows:

- It was proposed an organization of PLC MAC protocols into contention-free, contention based, and hybrid. Moreover, these protocols were also organized in terms of applications and main research focus.
- The main PLC standards were presented and described highlighting their characteristics at the link layer level.
- PLC MAC protocols were analyzed according to the suggested organization perspective in the scope of the main PLC applications.
- New research opportunities, challenges and future trends were identified and discussed in order to show the relevance and motivate the development of new MAC protocols for improving data communication at the link layer level of PLC systems.

3 DATA PACKET CORRECTION AT THE LINK LAYER LEVEL: A GENERIC APPROACH

In terms of physical and link layers, it is a valid statement that telecommunication systems are subject to problems that can severely degrade the data communication reliability. Indeed, the characteristics of the signal propagation as well as the additive noise in the communication medium jeopardize the performance of the data communication system by degrading and corrupting the transmitted signal. As a matter of fact, the specification and design of data communication system aim to overcome the limitations imposed by the chosen communication medium.

Wireless systems, for instance, have their transmitted signal propagation very dependent on the frequency band, the topography of the environment and on the conditions of the communication medium (e.g., air conditions) [232]. In fact, the data communication through the wireless medium is more prone to interferences in which the desired signal is combined with undesired ones transmitted on the same frequency, time or space [233,234]. Additionally, the propagation of the wireless signal can be impaired by obstacles between source and destination nodes [235]. Moreover, the presence of additive noise and of hidden terminals may also negatively impact on the wireless communication, degrading its reliability and performance [236–238].

On the other hand, a PLC system uses preexisting electric power grids, which were originally deployed for energy transmission and distribution, as data communication medium. Thus, the transmitted signal, in this medium, may suffer severe distortions because of the dynamic of loads; the occurrence of high-power impulsive noises; impedance mismatching at the point of connection between two cables and between a load and the power line. Furthermore, signal degradation is also noted because of cable breaking and aging, the use of electromagnetically unshielded cables, which result in induction of wireless signals into the power lines, and the increasing signal attenuation as the frequency or distance increase [60,78,239–241]. As a consequence, the reliability and the performance of data communication over PLC channels may be severely degraded.

In addition to the well-known strategies designed in the past 70 years to deal with the hardness of data communication medium, an appealing and novel strategy to handle the problems inherent to a data communication channel is the exploitation of the diversity concept [214]. For instance, the cooperative diversity is widely exploited through the use of amplify-and-forward (AF) and decode-and-forward (DF) protocols together with combining techniques at the physical layer level [69, 242–245]. Moreover, cooperative communication has been also investigated at the link layer level, because it can result in reliability and performance improvements without the need of modifying standardized physical layers [85, 246, 247].

However, when even the preexistent techniques and protocols are not enough to ensure data communication reliability between source and destination nodes of a data communication system, the latter may receive corrupted packets. In this case, the destination node requests packet retransmissions until it receives a correct copy of the transmitted packet. In the worst case in which all retransmissions fail, a packet loss may occur. In this regard, in order to avoid retransmission requests and packet losses, it is proposed, in the present chapter, a generic packet correction approach that is suitable for being applied to the link layer level. In accord with this approach, the correction is activated at the destination node, after the failure of the preexistent techniques and protocols and before the retransmission request. Moreover, as the proposed approach is designed to operate at the link layer level, it does not require modifications in the current standardized physical layers of telecommunication systems.

In sum, the major contributions, in the present chapter, are as follows:

- The proposal of a generic packet correction approach that works at the link layer level of data communication systems by using an arbitrary number of corrupted copies of a transmitted packet, stored in the destination node buffer. This proposal focuses on improving data communication reliability without imposing changes to standardized physical layers.
- A detailed analysis regarding the proposed approach limitations due to the use of the Majority Voting (MV) algorithm or of the brute force search (BFS) algorithm together with an error detection technique based on bitwise exclusive OR (XOR) operations.

In this sense, this chapter is organized as follows: Section 3.1 addresses assumptions, definitions and the studied scenario related to the present proposal. Section 3.2 describes the proposed protocol. Section 3.3 focuses on relevant information about the proposed protocol limitations and their probabilities. Finally, Section 3.4 provides a summary of the present chapter.

3.1 PROBLEM FORMULATION AND SYSTEM MODEL

Let a packet transmitted from a source node (S) to a destination node (D) of a data communication system be represented by a binary sequence with the length of N bits. More specifically, let $x \in \{0,1\}^N$ be the binary sequence transmitted by node S, which is affected by a, not necessarily, memoryless additive noise $v \in \{0,1\}^N$ and, as a consequence, node D receives the binary sequence $y \in \{0,1\}^N$. In other words, $y = x \oplus v$ in which $\oplus$ represents a XOR operation. Figure 9 depicts this transmission process. In this figure, the three dots vertically aligned represent the upper layers, the LINK and the

PHY labels refer to link and physical layers, respectively, of nodes S and D. Additionally, the continuous arrow indicates the transmission from node S to node D, the dashed arrow indicates the ARQ from node D to node S and the continuous line that connects nodes S and D represent a data communication link. Thus, still in Figure 9, note that a packet with $N = 6$ bits is transmitted and four of its binary positions are corrupted by v during the transmission process through the communication medium.

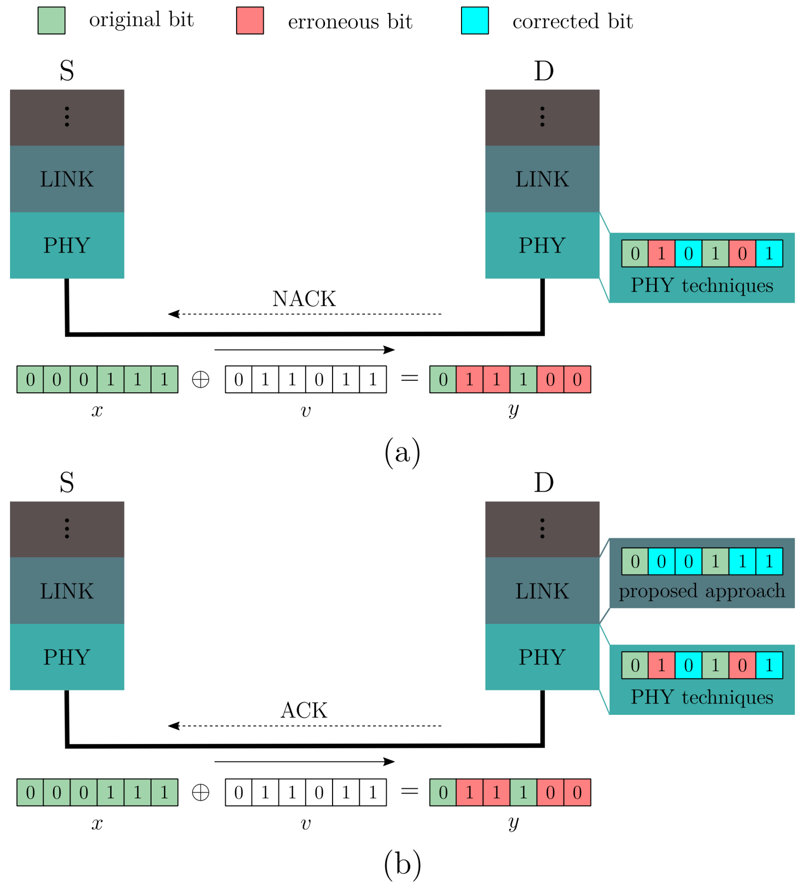


Figure 9: (a) The representation of the existing problem and (b) the representation of the proposal to deal with the existing problem.

Traditionally, when a corrupted packet is received by node D, physical layer techniques, such as forward error correction (FEC) [248], equalization and combining techniques [249], are applied in order to obtain the correct sequence of transmitted bits at the physical layer. However, as depicted in Figure 9.a, when physical layer techniques are not enough to assure the data communication reliability by correcting all the erroneous bits within the packet, a NACK is sent from node D to node S requesting the packet retransmission. The necessity of packet retransmissions is a problem when the existing data communication link is not reliable. A strategy to deal with this problem is to come up with approaches capable of avoiding retransmission requests and possible packet losses due to successive NACKs from retransmissions. In this sense, as shown in Figure 9.b, it is proposed an additional step of packet correction at the link layer level before retransmission requests. In the example from Figure 9.b, although physical layer techniques reduced the number of erroneous bits within the corrupted packet, they were not enough to assure the data communication reliability. Then, the proposed approach tries to correct, at the link layer level, the remaining two erroneous bits of the corrupted packet and, as a consequence, the retransmission request is avoided and an acknowledgment (ACK) message is sent from node D to node S.

A generic system model in which the proposed approach can be applied is shown in Figure 10. In this model, packets are transmitted from node S to node D through multiple links. More specifically, this model may be compared to a connected multigraph [250] $G(V, K)$ in which $G(.)$ represents the multigraph, V is the number of system nodes (the circles) and K is the number of links (the continuous lines) that interconnect these nodes. In this figure, it is possible to identify $V = 9$ nodes of which two of them (nodes S and D) represent source and destination nodes and the remaining nodes are relays (nodes R_1, R_2,...,R_{V-2}). Additionally, observe that there are $K = 13$ links interconnecting these V nodes. Moreover, $K' \in \mathbb{N}^*|K' \leq K$ is used to represent the degree of the node D ($K' = \deg(D)$), which corresponds to the number of links that interconnect nodes S and D (links SD). In this figure, $K' = 6$; however, this model can be expanded to any numbers of V and K.

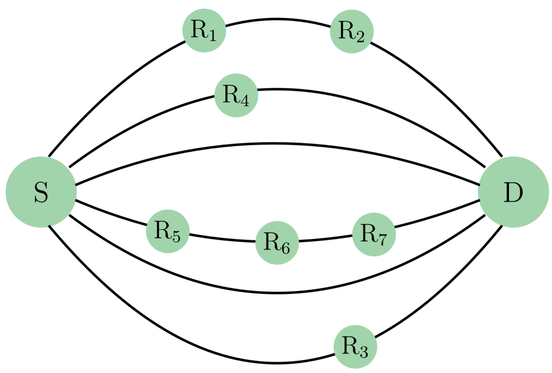


Figure 10: A multi-hop data communication system.

It is assumed that each of the k'-th links SD in which $k' \in \{1,...,K'\}$, has an associated $BER_{k'}$. More specifically, when a packet with the length of N bits is transmitted though the k'-th link, each bit of this packet may be corrupted with the probability defined by $BER_{k'}$. However, it is assumed that the ARQ and any other control message are immune to errors. In addition, each node has a reception buffer in which corrupted packets received are stored. It is assumed that the size of these reception buffers is big enough so that buffer problems do not occur (ideal buffer size). Additionally, it is assumed that every packet transmitted from node S is received by node D, corrupted or not. Moreover, it is assumed that node S is able to transmit, in parallel through distinct links SD, multiple copies of a given packet. Furthermore, it is assumed that the k'-ht link SD is associated with a delay $\tau_{k'}$, which is the time needed by a packet to leave node S and arrive at node D through the k'-th link SD. However, for the sake of simplicity, when multiple copies of a given packet are sent from node S to node D, it is assumed that the proposed approach is only activated after node D receives every copy, in case all of them are corrupted. It is further assumed the use of an interleaver at the physical layer level, which spreads apart encoded symbols in order to break the temporal correlation between successive symbols involved in a burst of errors [251, 252], because bursts of errors are likely to occur in data communication mediums, such as electric power grids.

3.2 THE PACKET CORRECTION APPROACH

In order to improve data communication reliability, distinct combinations of digital modulation, equalization and channel coding (i.e., the use of redundancy bits together with puncturing techniques) are common approaches at the physical layer level of data communication systems [253–256]. There are also cross-layer solutions, which involve physical and link layers, for correcting corrupted packets by using FEC, such as hybrid ARQ and MAC-FEC techniques [257–262]. However, redundancies used by the physical layer correcting codes are solved at the channel decoding block [263,264] and, as a consequence, in general, the medium access control protocol data unit (MPDU) received at the link layer level does not have these redundancies, although it usually has cyclic redundancy checking (CRC) fields according to its frame formats [53, 54, 189]. Thus, redundancy-free techniques are relevant research topics toward the proposal of correcting packets at the link layer level because it can avoid the necessity of changes in the standardized physical layer protocols.

As previously discussed, the main idea of the present chapter is to propose an approach that could be used at the link layer to improve the data communication reliability without requiring significant changes that could lead to modifications on standardized physical layers of data communication systems. In this sense, Figure 11 shows the flowchart for the proposed packet correction approach that is based on the combination XOR+BFS and on the MV algorithm. This approach is only applied in case the reception buffer has at least two corrupted copies of a given packet. When it starts, the reception buffer is verified. If it has more than two corrupted copies of a given packet (PKT), the majority voting algorithm is applied among all of these copies as a first packet correction attempt. In case it fails or if there are only two corrupted copies of the packet in the reception buffer, a correction attempt is performed by using the combination XOR+BFS. In other words, it is applied a bitwise XOR operation between an unverified pair of corrupted packets (i.e., a pair of corrupted packets that were not XORed yet) stored in the reception buffer, in order to detect their erroneous bits. Then, a BFS algorithm is applied in order to correct their erroneous bits. When the combination XOR+BFS fails, it is repeated by using another unverified pair of corrupted packets until it succeeds or until all combinations of corrupted packets from the reception buffer are used and the packet correction fails.

The selection of unverified pairs may use, for instance, SNR estimates so that the best pairs, in terms of SNR, are chosen with priority [265, 266]. Moreover, observe that the MV algorithm has priority over the combination XOR+BFS since the latter is used only if the former fails or if the reception buffer has only two corrupted copies of the packet. It is due to the fact that, in the worst case, the number of iterations of the BFS algorithm exponentially increases as the number of erroneous bits per packet increases.

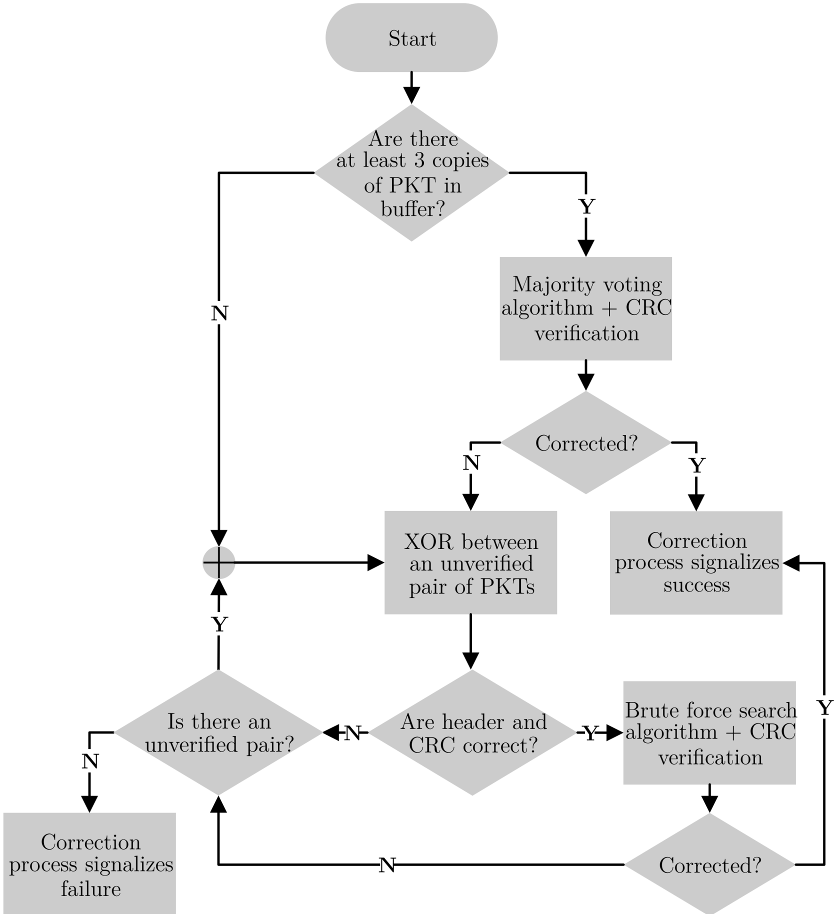


Figure 11: Flowchart of the proposed packet correction approach.

More specifically, the combination XOR+BFS has two main steps. Initially, it performs a bitwise XOR between two corrupted copies of a given packet from a given reception buffer in order to detect binary positions in which the bit value differs between these copies. It is assumed that these detected binary positions correspond to erroneous bits from both corrupted copies in which the bitwise XOR was applied. Then, a BFS algorithm is used for correcting these erroneous bits. In other words, if two erroneous bits were detected through the bitwise XOR operation, in the worst case, the BFS algorithm will test all $2^2 - 2$ possible combinations of values for these bits and verify the packet correctness by using the CRC after each tested combination. This example is depicted in Figure 12.a in which the horizontal darker rectangle represents the correct packet, vertical rectangles and dashed squares represent binary positions in which the bitwise XOR detects erroneous bits between the XORed packets.

Note that regardless of the number of corrupted copies of a packet within the reception buffer, it is recommended to use the bitwise XOR only between two of them. It is due to the fact that the bitwise XOR detects the sum of erroneous bits of all packets in which it is applied. For instance, if the bitwise XOR is being applied between two corrupted copies of a packet and if each of them has one erroneous bit in different binary positions between each other, two erroneous bits will be detected. Thus, if the correction of these two detected bits is enough to recover the packet, the use of more than two corrupted copies of the packet in the bitwise XOR would unnecessarily increase the number of erroneous bits to be corrected. It is possible to observe by comparing the number of erroneous bits detected in the examples of Figures 12.a and 12.b, which are represented by dashed squares. In this regard, when a given reception buffer has more than two corrupted copies of a given packet, it is important to choose the best two copies for applying the combination XOR+BFS. It could be done, for instance, by comparing the SNR information estimated at the receive related to each corrupted copy in the reception buffer.

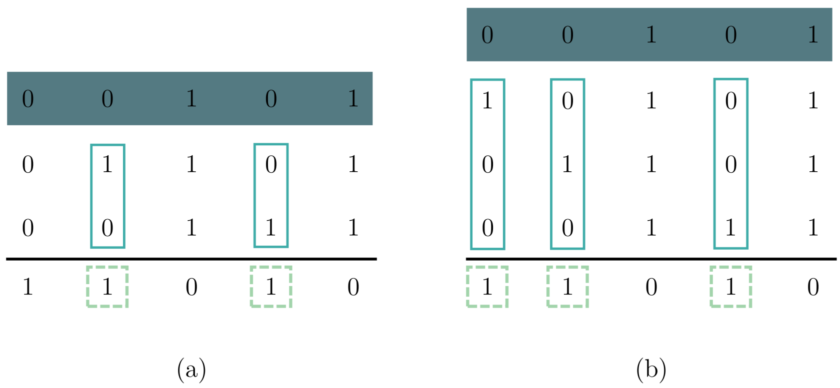


Figure 12: Examples of the detection of erroneous bits through the bitwise XOR operation.

On the other hand, the MV algorithm can be applied among all corrupted copies of a packet within the reception buffer. In summary, this algorithm verifies each binary position in which the bit values differ among all corrupted copies. The most frequent bit value of these verified positions is chosen as the correct one. Then, the CRC field is used to verify the packet correctness. Figure 13.a shows an example of the MV algorithm in which the horizontal darker rectangle represents the correct packet, vertical rectangles represent binary positions in which the bit values differ among corrupted copies of the packet and dashed squares represent the result chosen according to the most frequent bit value of each binary position. It is important to highlight that the MV algorithm is not recommended when there are only two corrupted copies of a packet in the reception buffer. It is due to the fact that, in this case, the binary positions in which the bit values differ will have a tie (i.e., equal number of zeros and ones in a given binary position). In a tie situation, the MV algorithm has the probability of 50% of choosing the wrong value and fail correcting the corrupted packet. Figure 13.b shows an example of the MV algorithm being used in just two corrupted copies of a packet. In this figure, the horizontal darker rectangle represents the correct packet, vertical rectangles represent binary positions in which the bit values differ among corrupted copies of the packet and dashed squares with a question mark represent the uncertain result due to tie occurrences.

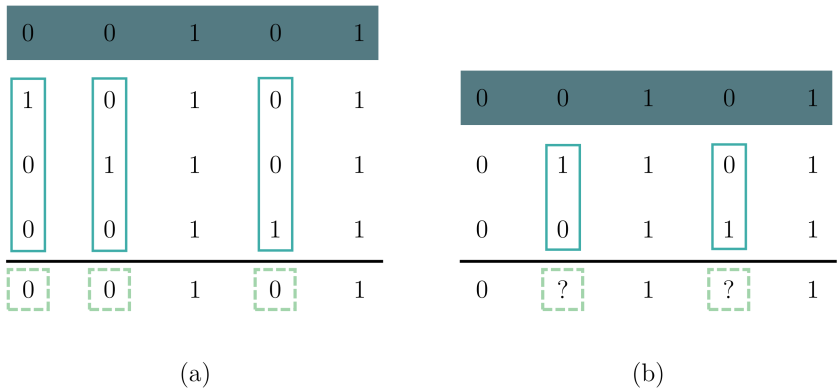


Figure 13: Examples of the MV algorithm.

In summary, the use of the combination XOR+BFS is an appealing packet correction alternative when it is possible to use two erroneous binary sequences with distinct error patterns due to the diversity offered by the data communication system. This diversity, which may be either obtained or exploited, for instance, through the use of cooperative protocols applied to hybrid systems such as the PLC-wireless [28,74,77], also benefits the use of the MV algorithm when more than two erroneous binary sequences are available. Thus, it is common to find, in the literature, proposals based on the combination XOR+BFS and on the MV algorithm for improving data communication reliability [211, 267–271]. However, these proposals are, usually, related with hybrid ARQ techniques or with extra packet correction blocks at the physical layer level after the channel decoding block. In contrast, it is proposed, in the present chapter, a generic approach that works entirely at the link layer level without requiring changes in standardized physical layers.

3.3 PACKET CORRECTION FAILURE PROBABILITIES

In this section, failure probabilities related to the packet correction through the combination XOR+BFS or the MV algorithm are discussed. Firstly, three distinct events that lead to the failure of the combination XOR+BFS are analyzed: $E_H = \{$there is at least one erroneous bit within the header field of one or both packets under the bitwise XOR operation$\}$, $E_C = \{$there is at least one erroneous bit within the CRC field of one or both packets under the bitwise XOR operation$\}$ and $E_P = \{$there is at least one undetectable erroneous bit within the packet payload$\}$. E_H and E_C occur after a bitwise XOR operation, when at least an erroneous bit is detected within the header or the CRC fields, respectively. On the other hand, E_P occurs when there is at least one erroneous bit in the same binary position between the packets under the bitwise XOR operation.

Note that, when there are $N_{nc} \geq 2$ corrupted copies of a given packet in a reception buffer, $C_{pair} = \binom{N_{nc}}{2}$ combinations can be used by the combination XOR+BFS before a packet correction failure. In other words, the combination XOR+BFS fails when E_H, E_C or E_C occur in all C_{pair} pairs of corrupted copies in which the combination XOR+BFS can be used.

Let $\text{PKT}_{pr,1}$ and $\text{PKT}_{pr,2}$ represent corrupted copies of a packet that composes the pr-th pair under the bitwise XOR operation in which $pr \in \mathbb{N}^*|pr \leq C_{pair}$. For instance, if a given reception buffer has three corrupted copies of a packet, $C_{pair} = \binom{3}{2} = 3$ is the number of pairs in which, in the worst case, the combination XOR+BFS will be applied. In this case, $pr \leq 3$ represents the pr-th pair so that $\text{PKT}_{1,1}$ and $\text{PKT}_{1,2}$ compose the first pair, $\text{PKT}_{2,1}$ and $\text{PKT}_{2,2}$ compose the second pair and $\text{PKT}_{3,1}$ and $\text{PKT}_{3,2}$ compose the third pair. Additionally, let $\epsilon_{pr,1}$ and $\epsilon_{pr,2}$ be equal to the bit error rate (BER) associated with $\text{PKT}_{pr,1}$ and $\text{PKT}_{pr,2}$, respectively. Then, the probability of E_H in the pr-th pair is given by

$$\begin{aligned}\mathbb{P}_{pr}(E_H) = \sum_{i=1}^{N_h} \binom{N_h}{i} \epsilon_{pr,1}^{i} (1-\epsilon_{pr,1})^{N_h-i} + \\ \sum_{i=1}^{N_h} \binom{N_h}{i} \epsilon_{pr,2}^{i} (1-\epsilon_{pr,2})^{N_h-i} - \\ \sum_{i=1}^{N_h}\sum_{j=1}^{N_h} \binom{N_h}{i}\binom{N_h}{j} \epsilon_{pr,1}^{i}\epsilon_{pr,2}^{j} (1-\epsilon_{pr,1})^{N_h-i}(1-\epsilon_{pr,2})^{N_h-j},\end{aligned} \tag{3.1}$$

in which N_h is the packet header length in terms of number of bits, i and j are the i-th and the j-th bits, respectively, of a given packet.

Analogously, the probability of E_C in the pr-th pair, $P_{pr}(E_C)$, can be obtained through the equation (3.1) by replacing N_h by N_c, which is the packet CRC length in terms of number of bits. Furthermore, the probability of E_P in the pr-th pair is given by

$$\mathbb{P}_{pr}(E_P) = \sum_{i=1}^{N_p} \binom{N_p}{i} \epsilon_{XOR_{pr}}^{i} (1-\epsilon_{XOR_{pr}})^{N_p-i}, \tag{3.2}$$

in which N_p is the packet payload length in terms of number of bits and $\epsilon_{XOR_{pr}} = \epsilon_{pr,1}\epsilon_{pr,2}$ is the probability in which erroneous bits are in the same binary position between the packets under the bitwise XOR operation and, as a consequence, these erroneous bits are undetectable.

Therefore, as the events E_H, E_C and E_P are not mutually exclusives, the probability in which the combination XOR+BFS fails to correct a corrupted packet by using its

pr-th pair of corrupted copies is given by

$$\begin{aligned}\mathbb{P}_{pr}(E_{XBF}) = \mathbb{P}_{pr}(E_H) + \mathbb{P}_{pr}(E_C) + \mathbb{P}_{pr}(E_P) - \\ \mathbb{P}_{pr}(E_H)\mathbb{P}_{pr}(E_C) - \mathbb{P}_{pr}(E_C)\mathbb{P}_{pr}(E_P) - \\ \mathbb{P}_{pr}(E_H)\mathbb{P}_{pr}(E_P) + \mathbb{P}_{pr}(E_H)\mathbb{P}_{pr}(E_C)\mathbb{P}_{pr}(E_P).\end{aligned} \tag{3.3}$$

Finally, the probability in which the combination XOR+BFS fails to correct a corrupted packet after using all C_{pair} combinations of its corrupted copies from a given reception buffer is given by

$$\mathbb{P}(E_{XBF}) = \prod_{pr=1}^{C_{pair}} \mathbb{P}_{pr}(E_{XBF}). \tag{3.4}$$

From now on, failure probabilities related with the MV algorithm are discussed. The MV algorithm fails due to two distinct and mutually exclusive events: $E_T = \{$there is a tie of votes at the i-th binary position among the packets under the use of the MV algorithm$\}$ and $E_M = \{$the majority of the votes at the i-th binary position among the packets under the MV algorithm are wrong$\}$.

Note that E_T may only occur when N_{nc} is even. In this case, if ϵ_{h1} is the probability in which $N_{nc}/2$ corrupted copies of a packet have an erroneous bit in a given binary position and ϵ_{h2} is the probability in which the remaining $N_{nc}/2$ of these corrupted copies have an erroneous bit in a given binary position, then, the probability in which E_T occurs is given by

$$\mathbb{P}(E_T) = \epsilon_{h1}(1 - \epsilon_{h2}) + \epsilon_{h2}(1 - \epsilon_{h1}). \tag{3.5}$$

When E_T occurs in a given binary position, the MV algorithm has the probability of 50% of choosing the wrong bit value for this position, which leads to a packet correction failure.

In terms of E_M, let ϵ_{m1} be the probability in which the majority of the corrupted copies (from $N_{nc}/2+1$ to $N_{nc}-1$) of a packet in a reception buffer have an erroneous bit in a given binary position. Furthermore, let ϵ_{m2} be the probability in which the remaining corrupted copies (from 1 to $N_{nc}/2-1$) of this packet have an erroneous bit in a given binary position. Thus, the probability in which E_M occurs is given by

$$\mathbb{P}(E_M) = \epsilon_{m1}(1 - \epsilon_{m2}) + \epsilon_{m1}\epsilon_{m2}. \tag{3.6}$$

Note that, when the MV algorithm is applied, E_T and E_M may occur in any binary position among the N_{nc} corrupted copies of a packet in a reception buffer. In this regard, the probability in which the MV algorithm fails is given by

$$\mathbb{P}(E_{MV}) = \begin{cases} 0.5 \sum_{i=1}^{N} \binom{N}{i} \mathbb{P}(E_T)^i (1-\mathbb{P}(E_T))^{N-i} + \\ \quad \sum_{i=1}^{N} \binom{N}{i} \mathbb{P}(E_M)^i (1-\mathbb{P}(E_M))^{N-i}, & \text{if } N_{nc} \text{ is even} \\ \sum_{i=1}^{N} \binom{N}{i} \mathbb{P}(E_M)^i (1-\mathbb{P}(E_M))^{N-i}, & \text{otherwise,} \end{cases} \tag{3.7}$$

in which N is the length of the corrupted copies of the packet in terms of number of bits.

Finally, the probability in which the proposed approach fails to correct a packet by using its corrupted copies from a reception buffer is given by

$$\mathbb{P}_{fc} = \begin{cases} \mathbb{P}(E_{XBF}), & \text{if } N_{nc} = 2 \\ \mathbb{P}(E_{MV})\mathbb{P}(E_{XBF}), & \text{if } N_{nc} > 2. \end{cases} \tag{3.8}$$

It is important to highlight that the proposed approach is used only if $N_{nc} \geq 2$, so that the equation (3.8) covers all valid N_{nc} values.

3.4 SUMMARY

The main contributions of the present chapter are summarized as follows:

- It was proposed a generic packet correction approach that works at the link layer level improving the reliability of the data communication by avoiding retransmissions or packet losses. Moreover, the proposed approach does not require the modification of standardized physical layers of data communication systems.
- The failure probabilities related to the MV algorithm and to the combination XOR+BFS, which are components of the proposed packet correction approach, were discussed.

4 EPLC-CMAC: AN ENHANCED COOPERATIVE MAC PROTOCOL FOR BROADBAND PLC SYSTEMS

PLC networks requires less investment in additional telecommunication infrastructure, since it works over preexisting electric power system infrastructure. However, the difficulty of exploiting the available resource of the electric power grids for data communication purpose is a disadvantage related to this kind of medium [72]. Currently, most of existing works address this disadvantage at the physical layer level. On the other hand, approaches at the link layer level, such as the use of cooperative protocols [272, 273] and ARQ techniques [274, 275], may also improve PLC system performance.

In this sense, in [85], it was proposed a cooperative medium access control (CMAC) protocol, named PLC-CMAC, that is capable of reducing packet loss ratio of a PLC system and of improving its goodput in comparison to a PLC system without cooperation at the link layer level. However, when the data communication fails even with the use of the PLC-CMAC protocol, retransmission requests and packet losses may occur. In this case, based on the generic approach proposed in Chapter 3, it is proposed, in the present chapter, the use of a packet correction technique, at the link layer level, together with a cooperative MAC protocol. More specifically, when the preexisting techniques and protocols are not enough to ensure the data communication reliability, the use of an additional packet correction attempt is proposed, at the link layer level of an in-home broadband PLC system, which can face its packets severely corrupted by the dynamics of electric power grids.

The proposed protocol, named EPLC-CMAC, uses system nodes as relays adaptively, according to their availability, to assist the data communication between source and destination nodes. Thus, the proposed protocol efficiently exploits the diversity of a single relay channel model to increase the reliability of in-home PLC systems at the link layer level. In addition, the adoption of a simple packet correction technique, at the link layer, allows the proposed protocol to recover corrupted packets, under a certain capacity, instead of simply discarding them and requesting retransmissions. In other words, the EPLC-CMAC protocol exploits relay availability for retransmitting packets and, when the relay assistance is not enough to prevent a packet loss, it applies a packet correction technique at the link layer.

In sum, the major contributions, in the present chapter, are as follows:

- The proposal of EPLC-CMAC, a new MAC protocol that efficiently merges a cooperative protocol and a packet correction technique, at the link layer level, when PLC systems based on OFDM and OFDMA schemes are considered.
- A detailed discussion of the EPLC-CMAC protocol by scrutinizing its limitations regarding the use of an error correction technique based on the BFS algorithm

together with an error detection technique based on the bitwise XOR operation.

- Comparative performance analyses of the proposed protocol (EPLC-CMAC) against the PLC-CMAC protocol [85] when the packet size varies, broadband PLC systems based on OFDM and OFDMA schemes and an additive noise model are considered.

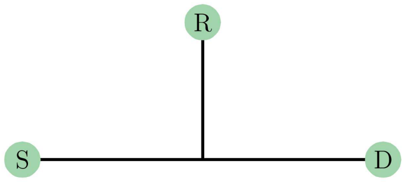
In this sense, this chapter is organized as follows: Section 4.1 addresses assumptions, definitions and studied scenarios related to the present proposal. Section 4.2 describes the proposed protocol. Section 4.3 focuses on relevant information about the proposed protocol limitations and their probabilities. Section 4.4 present numeric results and performance analyses. Finally, Section 4.5 provides a summary of the present chapter.

4.1 SYSTEM MODEL

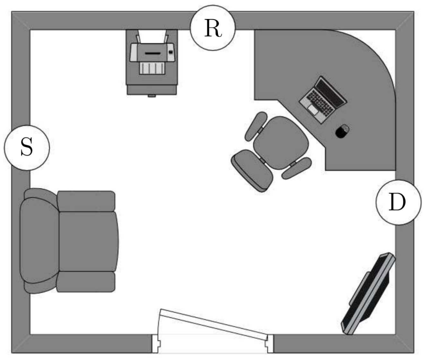
In this chapter, it is considered a cooperative in-home broadband PLC system using, but not limited to, a single relay channel model (see Figure 14.a). Figure 14.b shows a typical in-home scenario in which there are three outlets as network nodes. Note that, in these outlets, letters S, R and D denote source, relay and destination nodes, respectively. In this scenario, there are three links: source-destination (SD), source-relay (SR) and relay-destination (RD). It is assumed that each link has a packet error rate (PER) named as PER_k, where $k \in \{SD, SR, RD\}$. Additionally, PER_{SR} and PER_{RD} values are used from a scenario in which R position is equidistant from S and D, since it is the most appropriate scenario for relay-oriented MAC protocols, as shown in [69, 85, 276]. Moreover, in [85], authors give a more detailed description of the impact of the relay position in the cooperative MAC protocol performing relayed retransmissions. Furthermore, in [277], channel frequency responses of the considered in-home broadband PLC system are detailed.

4.1.1 MAC Frame Model

In terms of MAC sublayer, it is considered a TDMA scheme in which each user has two time-slots (see Figure 15), which is similar to the MAC frame structure proposed in [278]. The former time-slot corresponds to a signaling period (SP), which is used for exchanging control messages, while the latter corresponds to a data period (DP), which is applied for performing packets transmissions and receptions. Note that time-slot sizes are assumed big enough for transmitting packets with up to 100 bytes during SP and up to 500 bytes during DP. Furthermore, physical blocks with a body size of 500 bytes are considered to envelope packets from link layer, which is similar to the physical block size described in [53]. Thus, packets constituted by more than 500 bytes are fragmented and sent by using more than one MAC frame. It is also considered that, between two consecutive MAC frames, there is a contention-free inter frame space (CFIFS), which is



(a)



(b)

Figure 14: In-home single relay scenario.

the time needed for coordination purposes in the shared medium. Finally, it is assumed that the control messages (e.g, ARQ messages) are error-free and, thus, PER values refer only to data packets.

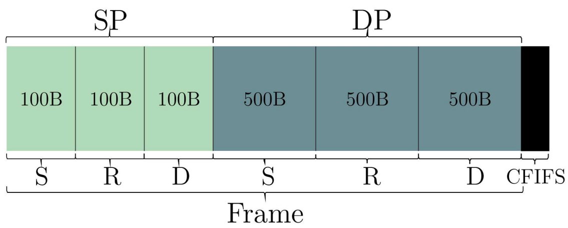


Figure 15: The TDMA scheme frame structure.

4.1.2 Impulsive Additive Noise Model

A simplified model of the impulsive additive noise at the output of the PLC channel is adopted, which is adequate to illustrate the worst possible scenario [58, 279]. The discrete-time domain representation of the adopted impulsive additive noise model is given by

$$v[n] = v_{background}[n] + v_{ps}[n] + v_{imp}[n] \tag{4.1}$$

in which $v_{background}[n] \sim \mathcal{N}(0, \sigma_v^2)$ represents the background noise, $v_{ps}[n] \sim \mathcal{N}(0, K_1\sigma_v^2)$ denotes the synchronous periodic impulsive noise, whose time of arrival of its impulses ($t_{arr,r} = 1/f_o$) is related to the power grid frequency ($f_o = 60$ Hz), $v_{imp}[n] \sim \mathcal{N}(0, K_2\sigma_v^2)$ refers to the asynchronous impulsive noise, whose inter-arrival time in the continuous-time domain between two consecutive impulses, $t_{arr,s}$, is an exponential random variable with a mean value of 100 ms. Furthermore, it is assumed that the duration of each synchronous periodic and aperiodic noise burst in the continuous-time domain is $t_{w,s} = 100\mu$s.

In order to calculate PER values, the BER, at the link layer, related to the k-th link, is considered by assuming that the sequence of bits, which compose a packet is a binary random process with two states: one state associated with the presence of background noise and the other one with the presence of the background noise plus the impulsive noise [280]. As a result, the PER value is given by

$$PER_k \approx 1 - \left[(1 - \eta BER_k)^{\nu N} + (1 - BER_k)^{(1-\nu)N}\right], \tag{4.2}$$

in which $\eta \in \mathbb{R}_+^*$ is an augment ratio that varies according to the noise in a given time interval (see Figure 16), $0 \leq \nu \leq 1$ and $N \in \mathbb{N}^*$ is the packet length in terms of number of bits. Note that the η value describes the presence or not of impulsive noise by increasing or decreasing the bit error rate. Moreover, νN and $(1-\nu)N$ refer to the subsequences of bits associated with the presence of the background noise plus the impulsive noise and background noise, respectively.

When the packet size is of more than 500 B, the packet fragmentation occurs due to the adopted physical block size. In this case, the PER value is given by $PER_k = \sum_{n_f=1}^{N_f} PER_{k,n_f}$ in which n_f identifies the fragment number, N_f is the total number of fragments and PER_{k,n_f} is the PER of the n_f-th fragment associated with the k-th link. Note that an equation similar to (4.2) applies to evaluate PER_{k,n_f}.

Figure 16 illustrates the impact of the additive noise in the bit error rate associated with k-th link (BER_k) when in-home PLC channels are considered. In this figure, the thick line along the t-axis represents the background noise and the vertical bars represent time intervals ($t_{w,s}$) in which there are impulsive noises. Note that, during the background noise, $\eta = 1$ and, during impulsive noises, $\eta = \eta_0 \gg 1$.

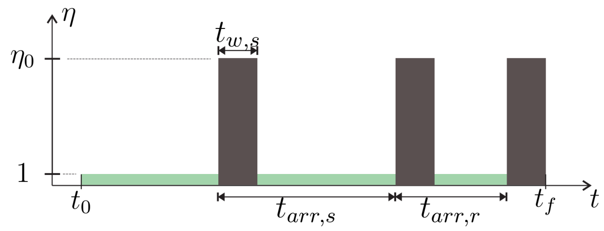


Figure 16: η values under background and impulsive noises.

4.2 THE EPLC-CMAC PROTOCOL

An enhanced cooperative MAC protocol, named as EPLC-MAC, which performs cooperative retransmissions through a neighbor node used as relay is proposed. In case of a NACK from a retransmission, the proposed protocol can, at the link layer level, detect

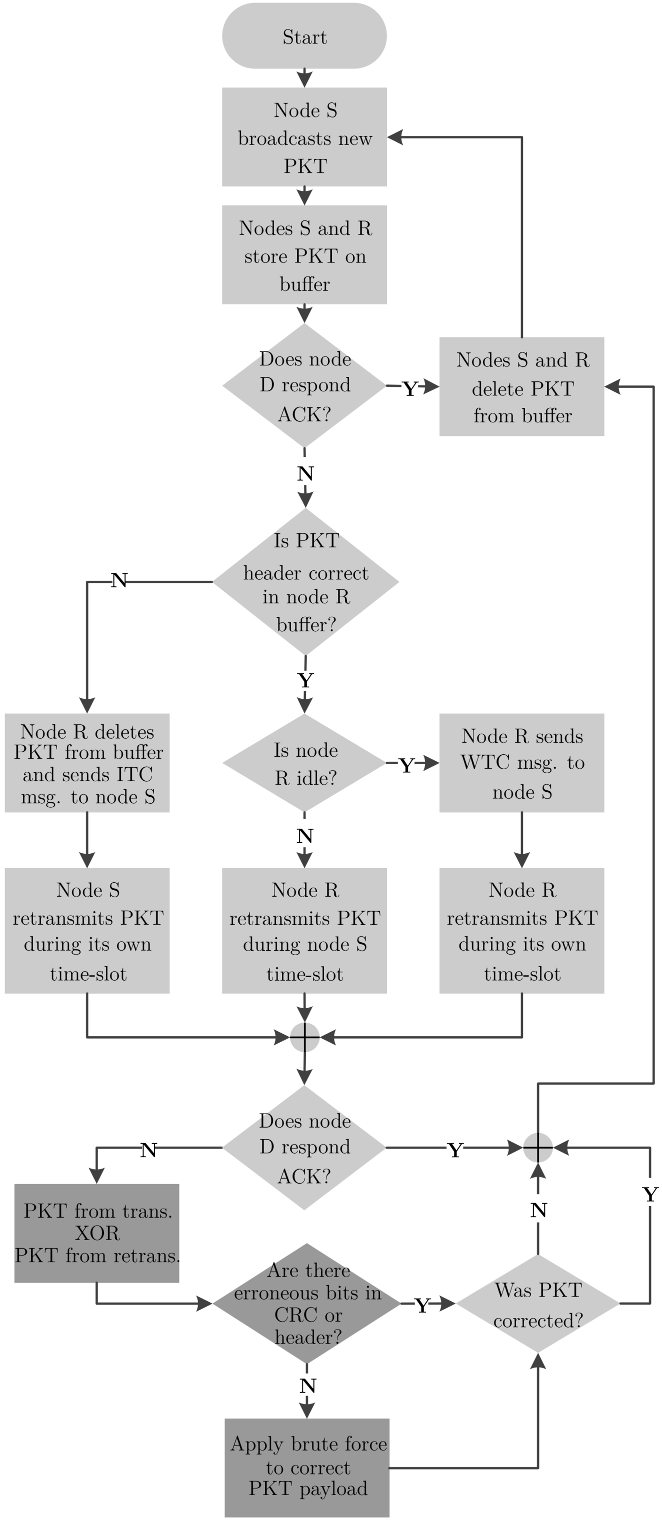


Figure 17: EPLC-CMAC protocol for in-home PLC systems based on TDMA-OFDM scheme.

erroneous bits and correct corrupted packets at the receiver. Note that, as the proposed protocol works at the link layer level, it can be used as an additional step to improve data communication reliability, when the techniques applied at the physical layer level are not enough to ensure the packet correctness.

Figure 17 shows the flowchart of the EPLC-CMAC protocol working in a TDMA-OFDM scheme. The proposed protocol starts when node S sends a packet (PKT) to node D, which is also received by node R. Both nodes, S and R, store this packet temporarily. In case node D replies node S with an ACK, both nodes S and R clear the stored packet within their buffers. Then, node S is able to send a new packet during its next time-slot. Otherwise, in the case of a NACK from node D, if node R is idle (i.e., it does not have packets for transmission during its next time-slot), it sends a *Want To Cooperate* (WTC) message to node S offering its own time-slot for carrying out cooperative communication at the link layer. Thus, if node S receives a WTC message from node R, PKT retransmission will occur during the next node R idle time-slot. As a consequence, node S is able to send a new PKT during its next time-slot. Note that, in this case, node R received a PKT with an error-free header field from node S transmission. Otherwise, node R would have to send an Impossible to Cooperate (ITC) control message to node S informing that, in case of retransmission, node S itself would need to retransmit the PKT through the link SD. It is due to the fact that the header field contains important information, such as the node D address, that needs to be intact in order to make the data communication feasible. In order to verify the header field integrity, it is assumed that it has a CRC field. Figure 18 shows the messages exchanging before packet retransmission. Note that the WTC/ITC messages are the only overhead added by this protocol, during SP.

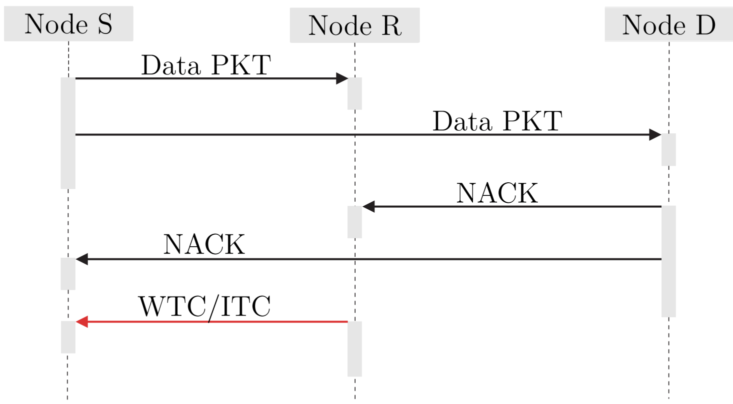


Figure 18: Messages exchanging before retransmission

When node R is not idle and, as a consequence, it is not able to offer its own time-slot for packet retransmission, but it has a copy of PKT with an error-free header field in its buffer, the EPLC-CMAC protocol operates regardless of the relay idleness by performing cooperation during the node S time-slot. In other words, node R will use the next node S time-slot to retransmit the packet through the link RD. As a consequence, node S is not able to use this time-slot to send a new PKT. However, the cooperative retransmission may improve the data communication reliability when compared to direct retransmission through the link SD. Observe that, regardless of the relay node idleness, the proposed protocol does not add messages overhead during DP. In fact, the proposed protocol asks for retransmissions during node R idle time-slot or during node S time-slot that was already reserved for packet retransmission.

Then, after node D receives the retransmission of the last packet, if all retransmissions fail, the use of the packet correction technique starts. The darker boxes of Figure 17 summarize the packet correction technique execution steps. Note that there is a verification of packet header and CRC integrity before using the BFS algorithm for correcting the erroneous bits in the received packet. If these fields are not correct, the error correction will not be effective (reliable) since the packet header carries its sender and receiver addresses and a corrupted CRC cannot be used to verify the packet correctness. Thus, in this case, packet correction process is aborted.

In sum, both PLC-CMAC [85] and EPLC-CMAC protocols use a cooperative communication approach at the link layer. However, if this cooperative communication approach fails, while in the former the packet is simply lost, in the latter it is used a packet correction technique at the link layer to handle this failure, which may reduce packet loss occurrences. Nevertheless, as only one retransmission attempt is considered, in case the packet correction technique also fails, there is a packet loss.

In order to understand how the packet correction technique works within the proposed protocol, let us assume the occurrence of a NACK in a transmission from node S to node D. In the case of using the TDMA-OFDM scheme, node R or node D retransmits this packet alone and, thus, the reception buffer of node D has two copies of the same packet (one received from the transmission and one received from the retransmission). On the other hand, using the OFDMA scheme[1], and assuming that node R has a copy of PKT with an error-free header field, node R retransmits packets together with node S during the same time-slot and, as a consequence, the reception buffer of node D has a set of three copies of the same packet (one from the first transmission, one from node S retransmission and one from node R retransmission). Figure 19 shows node D reception buffer when each aforementioned scheme is considered. In this figure, Tx, Rx_S and Rx_R are abbreviations of transmission, retransmission from node S and retransmission from node R, respectively.

In case all packets are corrupted, node D uses the combining technique in order to find erroneous bits. More precisely, this combining technique is performed always between two packets in node D reception buffer regardless of the use of TDMA-OFDM or OFDMA schemes, as shown in Figure 20. However, when the OFDMA scheme is considered, the combining technique is performed between a subset with two of the three packets in node D reception buffer. In this case, if the combination between the first two packets does not work, another subset of two packets is chosen and the process is

[1] More details of the PLC-CMAC protocol working with the OFDMA scheme is showed in [85].

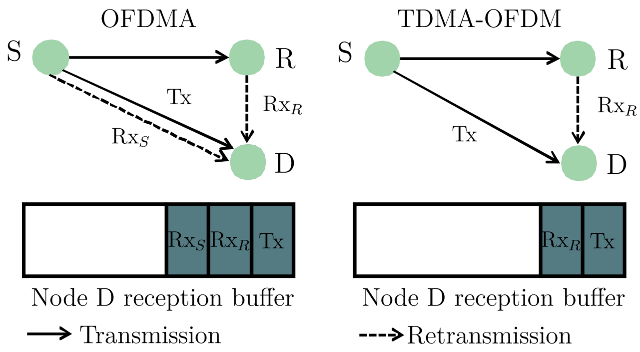


Figure 19: Node D buffer state.

repeated. In order to illustrate how the packet correction technique works, Figure 20 shows an example. As it is possible to note, there are three erroneous bits, which are detected by applying the bitwise XOR operation between bits located at the same position ($PKT_{q_i} = PKT_{ds_i} \oplus PKT_{dr_i}$, $i = 1, 2, ..., N$) of the packets ($PKT_{ds} \in \{0,1\}^N$, transmitted by node S, and $PKT_{dr} \in \{0,1\}^N$, retransmitted by node R in which i denotes the i-th element of vector PKT_{ds} or PKT_{dr}, which are constituted by a N-length binary sequence). After finding these bits, a BFS algorithm is applied, which tries all possible combinations of bits for the packet correction (for this example, there are $2^3 - 2$ possibilities considering the three erroneous bits). The CRC is applied after each try in order to verify the successful correction of the packet.

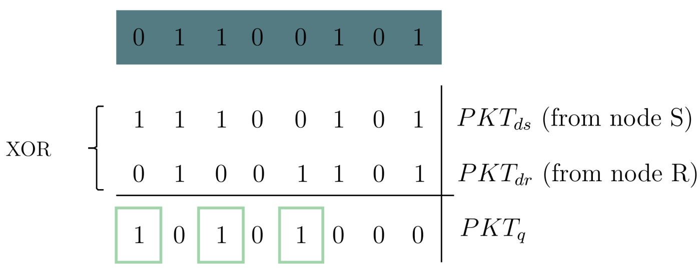


Figure 20: An example of the bit error detection at node D.

The use of this packet correction technique has two flaws. The first flaw is related to the exponential complexity of the BFS algorithm as the number of erroneous bits per packet increases. In the worst case, the BFS algorithm will execute $2^\gamma - 2$ correction attempts in which $\gamma \in \mathbb{N}^*$ is the number of erroneous bits that can be corrected by the packet correction technique. As an alternative to mitigate this problem inherent to the BFS algorithm, in [281], authors propose an algorithm that requires lower computational complexity for guessing the erroneous bits instead of trying all possible combinations in $2^\gamma - 2$ correction attempts. The latter flaw occurs when the bit error detection fails. It may happen if one or more bits are erroneous in the same position among the XORed packets. This situation cannot be handled by the proposed protocol, but it can be avoided by considering [269].

It is also important to emphasize that the proposed protocol is not limited to a single-relay channel model. The main requirement to extend the proposed protocol to a multi-hop scenario is the choice of the best relay node. In this sense, in [70, 282], authors investigate interesting approaches for choosing the best relay. In other words, the proposed packet correction technique can be applied to any other model in which at least two copies of the transmitted packet by node S are available in node D.

4.3 PACKET CORRECTION LIMITATIONS

In this section, packet correction technique failure causes and probabilities are identified. In this sense, a set of equations are presented in which ϵ_{PTx} is equal to the BER, at the link layer, during the transmission. More specifically, $\epsilon_{PTx} = BER_{SD}$. On the other hand, ϵ_{PRx} is equal to the BER, at the link layer, during the retransmission. In other words, $\epsilon_{PRx} = BER_{SD}$, when the retransmission occurs without cooperation, or $\epsilon_{PRx} = BER_{SRD}$, otherwise in which BER_{SRD} is the total BER associated with links SR and RD.

In sum, three problems that could cause packet correction failure are considered. The first one is the error detection failure, which occurs when the bitwise XOR operation is not enough to find all erroneous bits. The second one is the corruption of packet header or payload CRC fields, since they carry important information that cannot be lost. The third one is the violation of the constraint applied to the processing time interval T_P of the BFS algorithm (i.e., $T_P > T_C$ in which T_C is the time interval available for the packet correction attempts), which causes an abortion of the packet correction process.

4.3.1 Error detection failure

Let the event $E_D = \{$there is at least one undetectable erroneous bit within $PKT_q\}$ define the error detection failure. First of all, the error detection failure related to the occurrence of background noise is calculated. In this context, the probability in which E_D occurs is given by

$$\mathbb{P}(E_D) = \sum_{i=1}^{\gamma} \binom{N}{i} \epsilon_{XOR}^{i} (1 - \epsilon_{XOR})^{N-i}, \tag{4.3}$$

in which $\gamma \leq N$ is the number of erroneous bits and $\epsilon_{XOR} = \epsilon_{PTx}\epsilon_{PRx}$ is the probability in which erroneous bits are in the same binary position between the packets under the bitwise XOR operation and, as a consequence, these erroneous bits are undetectable. It is important to emphasize that if PKT_q has at least one undetectable erroneous bit, then the BFS algorithm will not be able to correct the corrupted packet.

From now on, it is calculated the error detection failure when the impulsive noise occurs. In this sense, let $PKT_{ds} \in \{0, 1\}^N$ and $PKT_{dr} \in \{0, 1\}^N$ denote random packets received by node D from node S transmission and from node R retransmission, respectively; both PKT_{ds} and PKT_{dr} are corrupted copies of the packet $PKT_s \in \{0,1\}^N$ transmitted by node S; PKT_{ds} and PKT_{dr} are constituted by independent and random binary variables, see [280]. Moreover, it is assumed the following definition:

Definition 1: The modified Hamming distance between two N-length binary sequences, $d_{mH} \in \mathbb{N},\ 2 \leq d_{mH} \leq N$, is equal to the number of ***consecutive*** *binary positions in both sequences in which the corresponding bits are different.*

Therefore, the d_{mH} of PKT_{ds} in relation to PKT_s, $d_{mH}(PKT_s, PKT_{ds})$, identifies the number of consecutive erroneous bits (i.e., the size of the burst of errors) in PKT_{ds}. Analogously, $d_{mH}(PKT_s, PKT_{dr})$ identifies the size of the burst of errors in PKT_{dr}. Additionally, it is assumed that the $t_{arr,r}$ and the $t_{arr,s}$, defined in Section 4.1.2, are long enough to assure that each packet has a maximum of one burst of errors due to the impulsive noise.

The error detection failure occurs if $d_{mH}(PKT_{ds}, PKT_{dr}) < d_{mH}(PKT_s, PKT_{ds}) + d_{mH}(PKT_s, PKT_{dr})$. In other words, there is an error detection failure when there are undetectable bursts of errors (i.e., at least one burst of overlaps between PKT_{ds} and PKT_{dr}). The size of the undetectable bursts of errors is denoted as d_{mH_u} and it is given by $d_{mH_u} = (d_{mH}(PKT_s, PKT_{dr}) + d_{mH}(PKT_s, PKT_{ds}) - d_{mH}(PKT_{ds}, PKT_{dr}))/2$. Note that the error detection fails when $d_{mH_u} > 0$. In this regard, the probability of d_{mH_u} assuming a given value $l_\gamma \in \mathbb{N},\ 2 \leq l_\gamma \leq N$ is given by

$$\mathbb{P}(d_{mH_u} = l_\gamma) \leq (N - (l_\gamma - 1))\mathbb{P}_{el}^1 1^{l_\gamma - 1}(1 - \mathbb{P}_{el})^{N - l_\gamma}, \tag{4.4}$$

in which $\mathbb{P}_{el} = \eta^2 \epsilon_{XOR}$ is the probability of the leftmost bit of a given burst of errors being undetectable when an augment ratio η on ϵ_{PTx} and on ϵ_{PRx} is considered during the impulsive noise according to Section 4.1.2. Note that the $\mathbb{P}(d_{mH_u} = l_\gamma)$ is an upper bound, because the worst case is considered in which it is assumed $\mathbb{P}_{el}^{l_\gamma} = \mathbb{P}_{el}^1 1^{L_\gamma - 1}$. In other words, the probability of an entire burst of errors being undetectable is defined by the probability in which its leftmost bit is undetectable.

Finally, the probability $\mathbb{P}_{failure}$ of error detection failure by considering both background and impulsive noises is given by

$$\mathbb{P}_{failure} \leq \mathbb{P}(E_D) + \mathbb{P}(d_{mH_u} = l_\gamma) - \mathbb{P}(E_D)\mathbb{P}(d_{mH_u} = l_\gamma). \tag{4.5}$$

Note that, when there is an error detection failure, the BFS algorithm may result in a false correction result. It may occur when the undetectable erroneous bits are within the payload CRC field. In this case, the BFS algorithm may find a combination that the corrupted payload CRC field approves, but it is, otherwise, incorrect. The probability of the undetectable erroneous bits being within the payload CRC field, which may lead to a false correction, is given when N is replaced by the payload CRC field size in equations (4.3) and (4.4). As a result, an equation similar to the equation (4.5) is used to evaluate this probability.

4.3.2 Corrupted packet header or payload CRC

As shown in Figure 17, the EPLC-CMAC protocol only performs the BFS algorithm if there are not erroneous bits in the packet header or in the packet payload CRC. In fact, the packet header and payload CRC are fields in which erroneous bits lead to packet correction failure. The former has important information, such as transmitter and receiver addresses, that cannot be corrupted to ensure the feasibility of the data communication. The latter is used to check packet correctness after the use of the BFS algorithm. Note that the use of payload CRC could be replaced by another approach; however, its choice is in the interest of complying with existing MAC sublayer protocols and, as a consequence, to facilitate their adaptation to run the EPLC-CMAC protocol.

Let $E_{SH} = \{$there is at least one erroneous bit within the header of a given packet$\}$ and $E_{SC} = \{$there is at least one erroneous bit within the packet CRC field of a given packet$\}$. During a transmission, the header error probability ($\mathbb{P}_{bn}(E_{SH})$) and the payload CRC error probability ($\mathbb{P}_{bn}(E_{SC})$), during de background noise, are given by

$$\mathbb{P}_{bn}(E_{SH}) = 1 - (1 - \epsilon_{PTx})^{N_h} \tag{4.6}$$

and

$$\mathbb{P}_{bn}(E_{SC}) = 1 - (1 - \epsilon_{PTx})^{N_c}, \tag{4.7}$$

respectively, in which N_h and N_c means number of bits of the packet header and packet payload CRC, respectively. During a retransmission, $\mathbb{P}_{bn}(E_{SH})$ and $\mathbb{P}_{bn}(E_{SC})$ are obtained from the equations (4.6) and (4.7), when ϵ_{PTx} is replaced by ϵ_{PRx}.

During the impulsive noise, in a packet transmission, it is considered the worst case in which the error probability of an entire burst with the size of $\gamma > 1$ bits is given by

$$\mathbb{P}(d_{mH} = \gamma) = (\eta\epsilon_{PTx})^1 1^{\gamma-1}, \tag{4.8}$$

in which η is defined in Section 4.1.2. and ϵ_{PTx} is replaced by ϵ_{PRx} during a retransmission. As a consequence, the probability of the header field having a burst of $2 \leq \gamma \leq N_h$ erroneous is an upper bound given by

$$\mathbb{P}_{in}(E_{SH}) \leq \sum_{\gamma=2}^{N_h} \mathbb{P}(d_{mH} = \gamma). \tag{4.9}$$

Analogously, the probability of the payload CRC field having a burst of $2 \leq \gamma \leq N_{CRC}$, during the impulsive noise, is given by

$$\mathbb{P}_{in}(E_{SC}) \leq \sum_{\gamma=2}^{N_c} P(d_{mH} = \gamma). \tag{4.10}$$

Therefore, the total probability of erroneous bits within the header field and within the payload CRC field is given by

$$\mathbb{P}(E_{SH}) \leq \mathbb{P}_{bn}(E_{SH}) + \mathbb{P}_{in}(E_{SH}) - \mathbb{P}_{bn}(E_{SH})\mathbb{P}_{in}(E_{SH}) \tag{4.11}$$

and

$$\mathbb{P}(E_{SC}) \leq \mathbb{P}_{bn}(E_{SC}) + \mathbb{P}_{in}(E_{SC}) - \mathbb{P}_{bn}(E_{SC})\mathbb{P}_{in}(E_{SC}). \tag{4.12}$$

Thus, the probability $\mathbb{P}_{SHSC}$ in which there is at least one erroneous bit within a packet header or payload CRC, which leads to a packet correction failure, is given by

$$\mathbb{P}_{SHSC} \leq \mathbb{P}(E_{SH}) + \mathbb{P}(E_{SC}) - \mathbb{P}(E_{SH})\mathbb{P}(E_{SC}). \tag{4.13}$$

4.3.3 T_P exceeds T_C

In Section 4.2, it was presented the EPLC-CMAC protocol, which uses a BFS algorithm for packet correction. Therefore, it is possible to infer that the execution of this algorithm requires a processing time interval (T_P), which varies according to the number of erroneous bits in the packet and the processing capacity of the hardware used to implement the PLC transceiver.

In the present chapter, the focus is not on specifying hardware. Thus, it is assumed the use of a dedicated hardware that applies the packet correction technique in parallel with TDMA scheme frames, and its use is limited by an arbitrary processing time interval T_P. Moreover, it is assumed that this hardware is not capable of performing more than one packet correction at the same time, which represents the worst scenario. Therefore, T_P starts after a NACK from a retransmission (see Figure 17) and it needs to end before the occurrence of a second NACK from a retransmission. In other words, if this time interval between two consecutive NACKs from retransmissions is defined as T_C (time available for packet correction), then the packet correction only succeeds if $T_P \leq T_C$ (T_C is the upper bound of T_P).

Figure 21 shows T_C calculation in three different cases. In this figure, T_F means frame time interval, T_{IFS} means inter-frame space time interval (CFIFS duration), NC_{ACK} is the number of consecutive ACKs and P_{ACK} is the ACK probability. Additionally, in this figure, it is considered that node S has three distinct packets to transmit (PKT_1, PKT_2 and PKT_3). In case of a transmission NACK, the packet is retransmitted once and, in case of a NACK from a retransmission, the packet correction attempt starts, as it was detailed in Section 4.2. In this regard, T_C is given by one of the following approximations:

- The best case: after the first retransmission NACK, which represents the first packet correction need, only transmission ACKs occur. Hence, the packet correction technique is not needed again and, thus, T_C is maximum. In this case, $T_C = NC_{ACK}(T_F + T_{IFS}) + T_{IFS} = T_{best}$.

- The worst case: all transmissions and retransmissions fail. This case represents the shortest T_C time interval. It starts after the first retransmission NACK, when there is the first packet correction need, and ends after the second retransmission NACK, when there is a second packet correction need. In this case, $T_C = 2(T_F + T_{IFS}) = T_{worst}$.

- The realistic case: there are ACKs and NACKs transmissions according to a probability $P_{ACK} = 1 - PER_k$. In this case, $T_{worst} \leq T_C \leq T_{best}$.

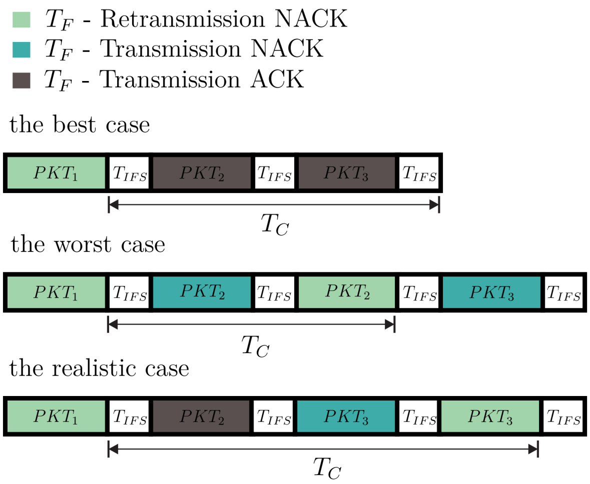


Figure 21: Details of the time intervals available for packet correction.

Regardless of the aforementioned cases, in the following analyses, it is assumed that the T_C is enough to guarantee the correction of γ_0 erroneous bits of a packet with γ erroneous bits. In this sense, it is assumed that the T_P variation is directly proportional to the number of erroneous bits (γ) detected in the packet PKT_q based on the evaluation of $PKT_{q_i} = PKT_{ds_i} \oplus PKT_{dr_i}$, $i = 1, ..., N$. It was previously defined $\epsilon_{XOR} = \epsilon_{PTx}\epsilon_{PRx}$, which determines the probability of an undetected erroneous bit in PKT_q, during the background noise. Analogously, let $\epsilon_{det} = \epsilon_{PTx}(1-\epsilon_{PRx})+(1-\epsilon_{PTx})\epsilon_{PRx}$ be the probability in which an erroneous bit is detected in PKT_q, during the background noise. In other words, ϵ_{det} is the probability in which an erroneous bit is not in the same binary position between the packets under the bitwise XOR operation. On the other hand, during the impulsive noise, it was previously defined $d_{mH}(PKT_{ds}, PKT_{dr})$ as the size of a burst of erroneous bits detected by $PKT_q = PKT_{ds} \oplus PKT_{dr}$.

If the dedicated hardware is capable of correcting up to $\gamma_0 > 0$ erroneous bits in the packet PKT_q with size N before T_C expires ($T_P \leq T_C$), then, the probability of

$\gamma \leq \gamma_0$, in PKT_q, during the background noise, is given by

$$\mathbb{P}_{bn}(\gamma \leq \gamma_0) = \sum_{\gamma=1}^{\gamma_0} \binom{N}{\gamma} \epsilon_{det}^{\gamma}[1 - \epsilon_{det}]^{N-\gamma}, \tag{4.14}$$

and, during the impulsive noise, it is given by

$$\mathbb{P}_{in}(\gamma \leq \gamma_0) \leq \sum_{\gamma=2}^{\gamma_0} \mathbb{P}(d_{mH} = \gamma), \tag{4.15}$$

in which $\mathbb{P}(d_{mH} = \gamma)$ is given by the equation (4.8). Note that $\mathbb{P}_{in}(\gamma \leq \gamma_0)$ may only exist if $\gamma > 1$ and $\gamma_0 > 1$. In this case, the probability of $\gamma \leq \gamma_0$, in PKT_q, is given by

$$\mathbb{P}(\gamma \leq \gamma_0) \leq \mathbb{P}_{bn}(\gamma_1 \leq \gamma_0) + \mathbb{P}_{in}(\gamma_2 \leq \gamma_0) - \mathbb{P}_{bn}(\gamma_1 \leq \gamma_0)\mathbb{P}_{in}(\gamma_2 \leq \gamma_0), \tag{4.16}$$

in which γ_1 is the number of erroneous bits detected during the background noise, γ_2 is the number of erroneous bits detected during the impulsive noise and $\gamma = \gamma_1 + \gamma_2$.

Moreover, the probability of $\gamma > \gamma_0$ and, as a consequence, $T_P > T_C$ in the packet under correction is given by $\mathbb{P}(\gamma > \gamma_0) \leq 1 - \mathbb{P}(\gamma \leq \gamma_0)$. In this case, the packet error may be corrected if the right combination of bits is performed in the first $2^{\gamma_0} - 2$ BFS attempts. For example, a hardware able to correct up to 2 bits or $\gamma_0 = 2$ (i.e., T_P is enough to correct two bits) receives a packet with 3 erroneous bits ($\gamma = 3$). It means that this hardware can perform the maximum of $2^2 - 2$ BFS iterations during T_C. However, this packet needs $2^3 - 2$ BFS iterations for its correction in the worst case. Generally speaking, the packet may be corrected with the probability of $(2^{\gamma_0} - 2)/(2^{\gamma} - 2)$ in which the BFS algorithm succeeds correcting it in the first $2^{\gamma_0} - 2$ iterations.

Therefore, the probability $\mathbb{P}_{enc}$ in which the BFS algorithm was not capable of correcting $\gamma > \gamma_0$ bits in a time interval shorten than T_P is given by

$$\mathbb{P}_{enc} \leq \mathbb{P}(\gamma > \gamma_0)\left(1 - \frac{2^{\gamma_0} - 2}{2^{\gamma} - 2}\right), \tag{4.17}$$

4.4 PERFORMANCE ANALYSES

This section focuses on comparatively evaluating the performances of in-home PLC system using EPLC-CMAC or PLC-CMAC and an in-home PLC system without any cooperative MAC protocol or packet correction technique. Specifically, the EPLC-CMAC protocol is analyzed in order to show what kind of improvements can be obtained by using a packet correction technique at the link layer of an in-home PLC system based on TDMA-OFDM and OFDMA schemes when a cooperative MAC protocol is applied.

4.4.1 Simulation Assumptions

First of all, for the sake of simplicity, N values are converted into bytes (N_b). Thus, N_b is varied from 50 to 1500 bytes in order to analyze the impact of the proposed protocol in different formats of data messages. Also, N_h and N_c are equal to 144 bits and 32 bits, in this order, which are similar to [53]. Furthermore, in order to carry out performance comparisons, the data communication reliability is analyzed through packet loss ratio (α) results. This parameter is given by

$$\alpha = \frac{Q_{PL}}{Q_{PTx}}, \tag{4.18}$$

in which Q_{PL} refers to the number of lost packets, Q_{PTx} refers to the number of packets sent by node S to node D.

Moreover, to acquire the values of Q_{PL}, Q_{PTx} and the number of erroneous bits per packet γ, transmissions of packets from node S to node D were simulated. In these transmissions, PER values were considered according to the background noise as well as the impulsive noise in the single relay channel model described in Section 4.1.

During the impulsive noise occurrences, BER augment ratios (η) of 10^1 and 10^2 were considered in relation to a BER value around 10^{-4} found when the data communication occurs in the PLC channel corrupted by only the presence of the background noise. These BER were chosen in order to simulate the worst case with poor channel conditions. Furthermore, the occurrence of an erroneous bit due to the augmented BER, during the impulsive noise, lead to a burst of correlated erroneous bits. More specifically, in a burst with d_{mH} erroneous bits, the error rate of the first bit is the augmented BER and the error rate of the next $d_{mH} - 1$ erroneous bits is 1, which is the worst case.

The simulation was repeated for packet sizes varying from 50 to 1500 bytes. However, it is considered a physical block body size of 500 bytes during DP, as also described in Section 4.1, which is similar to [53]. Thus, packets containing more than 500 bytes are fragmented and their fragments are sent during several MAC frames (e.g., the transmission of a 1500 bytes packet takes three MAC frames intervals). The results presented in this section consider this fragmentation. Nevertheless, the packet correction technique is applied only when a given packet is complete at the receiver. As a consequence, this fragmentation does not affect the proposed models of sections 4.1 and 4.3, with the exception of the impulsive noise model. When there is an impulsive noise, the packet fragmentation may alleviate its impact. It is due to the fact that, when a packet is fragmented, an impulsive noise, which could affect an entire packet within its entire duration, may affect only a 500 B fragment of this packet. These considerations regarding the impulsive noise were discussed in Section 4.1.2.

Additionally, it is considered the use of TDMA-OFDM and OFDMA schemes at physical layer. Also, the AF is considered as the default scheme at the node R, because it is the worst scenario in which the proposed protocol needs to reduce the α even when node R may forward corrupted packets. Moreover, it is adopted T_C of the realistic case presented in Section 4.3.3, which represents a common behavior in a real situation. In case of cooperation at the link layer, it is assumed that node R is always available to help node S retransmission. Furthermore, it was considered that system nodes make use of ideal buffers with sufficient size to ensure that buffer overflow is an impossible condition.

Furthermore, values of α of the proposed protocol were analyzed by considering correlation probabilities P_{corr} between the PKT_{rs} and PKT_{ds}. PKT_{rs} is a copy of PKT_s, corrupted or not, stored in node R buffer after its transmission from node S. Analogously, PKT_{ds} is also a copy of PKT_s, corrupted or not, stored in node D buffer after its transmission from node S. It is assumed that there is correlation between PKT_{rs} and PKT_{ds} when they have erroneous bits in the same binary positions between each other according to P_{corr}. More specifically, P_{corr} values of 0.25, 0.50, 0.75 and 1 were considered for different values of N_b.

Finally, α results were generated by considering a set of hardware capacities in terms of bit correction, during T_C, from 1 to 20 bits, as it was not defined a specific hardware for the use of the packet correction technique of the EPLC-CMAC protocol. Also, equations (4.3)-(4.17) were adopted to analyze the correction capacity of the proposed protocol over the simulations. Table 4 summarizes the details of the simulations performed in the MATLAB software.

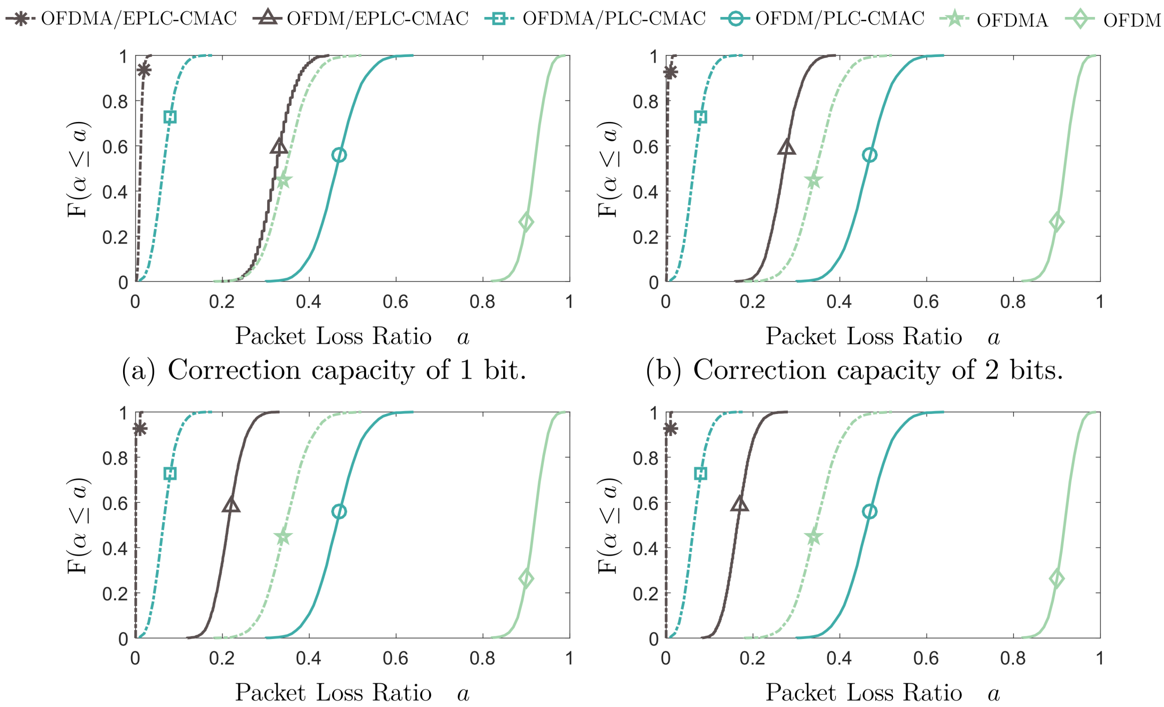
Table 4: Simulation parameters.

Parameter	**Value**
BER	10^{-4}
Packet size (bytes)	50, 100, 250, 500, 1000, 1500
Number of transmissions	10^5
Number of simulations	100
T_C	from 1 to 20

4.4.2 Numerical Results

First of all, according to [85], the OFDMA scheme results tend to be better than the ones related to the TDMA-OFDM scheme in all simulations that involve cooperative communication. In fact, for the former scheme, in case of NACK reception from node D, a cooperative protocol, at the link layer, is able to perform data retransmissions simultaneously by nodes S and R. Nevertheless, in the latter scheme, just node R retransmits data.

Figure 22 shows cumulative distribution functions (CDFs) of the α from a set of simulations considering PLC systems with the EPLC-CMAC protocol, PLC systems with the PLC-CMAC protocol and PLC systems without any cooperative protocol and any packet correction technique. More specifically, each time the simulations were repeated, for each of the aforementioned scenarios, their α were calculated through the equation (4.18). In this sense, the y-axis shows the frequency in which $\alpha \leq a$, for each a value from the x-axis. This first analysis focuses on investigating the impact of a limited packet correction capacity on the proposed protocol results. In this regard, it is used a fix packet size of 500 B, which is the maximum packet size that can be transmitted during each time-slot, and, then, it is varied only the packet correction capacity from 1 to 4 bits. As packet losses are under analysis, it is worth mentioning that the results are better if the curves are closer to y-axis in which the α is lower.



(a) Correction capacity of 1 bit.

(b) Correction capacity of 2 bits.

(c) Correction capacity of 3 bits.

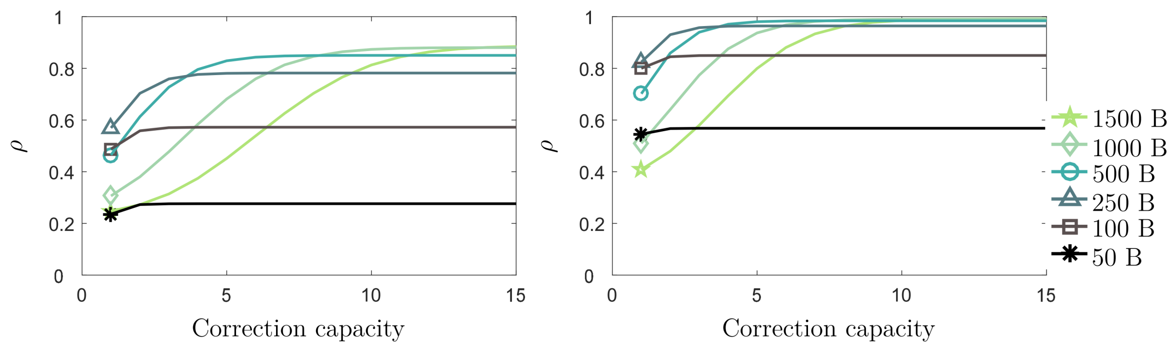
(d) Correction capacity of 4 bits.

Figure 22: CDFs of the packet loss ratio results considering different hardware correction capacities. (- - -) dashed and (—) continuous curves are associated with OFDMA and OFDM schemes, respectively.

Note that the EPLC-CMAC protocol (EPLC-CMAC) improves system reliability regardless of the adopted scheme and the correction capacity. In fact, all performance curves related to the proposed protocol are far to the left in comparison to the others, even in the worst scenario in which the bit correction capacity is of just one bit (Figure 22.a)). In other words, the use of a packet correction technique at the link layer reduces the probability of occurrence of a packet drop. As a consequence, the number of successful corrections increase and the data communication reliability improves. Moreover, as it is expected, the OFDMA scheme surpasses the OFDM scheme, since the curves of the former are closer to the y-axis than the correspondent curves of the latter, for the aforementioned reasons.

In the following analysis, results of the EPLC-CMAC protocol are compared with the ones associated with the PLC-CMAC protocol. In this sense, it is evaluated the mean packet loss ratio reduction (ρ), which is given by $\rho = \left(\mathbb{E}\{\alpha_0\} - \mathbb{E}\{\alpha_f\}\right)/\mathbb{E}\{\alpha_0\}$ in which $\mathbb{E}\{\alpha_0\}$ is the mean α value for using the PLC-CMAC protocol in a set of simulations, while $\mathbb{E}\{\alpha_f\}$ is the mean α value associated with the use of the EPLC-CMAC protocol in another set of simulations. Note that $\mathbb{E}\{\cdot\}$ denotes the expectation operator.

Figure 23 shows ρ for each value of bit correction capacity in different packet sizes. Note that ρ achieves higher values for bigger packet sizes (e.g., ρ maximum values are of 0.88 and 0.27 for packet sizes of 1500 bytes and 50 bytes, respectively, with the use of the TDMA-OFDM scheme). In fact, the bit error incidence is higher in longer packets and, as a consequence, the packet correction technique is more relevant. Moreover, it is noted that each performance curve shows the correction capacity upper bound, from which ρ assumes a constant value. This upper bound represents the correction capacity in which ρ achieves its best results from packets with a number of bytes equal to N_b that can be recovered by using the proposed protocol. Note that, as N_b increases, the upper bound is shifted to the right, representing a higher correction capacity requirement. In fact, in the TDMA-OFDM scheme (Figure 23.a), ρ achieves its maximum value requiring packet correction capacities of at least 3, 4, 6, 9, 13 and 15 bits for $N_b \in \{50, 100, 250, 500, 1000, 1500\}$ bytes. On the other hand, in the OFDMA scheme (Figure 23.b), as it is expected, ρ reaches its maximum values requiring lower correction capacities of at least 2, 3, 5, 6, 9 and 13 bits to the aforementioned packet size values, when compared to the ones showed in Figure 23.a.



(a) TDMA-OFDM scheme. (b) OFDMA scheme.

Figure 23: Mean packet loss ratio reduction due to the use of the EPLC-CMAC protocol in relation to the use of the PLC-CMAC protocol.

Figure 24 shows mean α ($\mathbb{E}\{\alpha\}$) results (y-axis) from a set of simulations related to the use of the proposed protocol with the TDMA-OFDM scheme under seven distinct cases of study (x-axis), as detailed in Table 5. Figure 24 also shows error bars with the confidence interval, for a confidence level of 99%. Additionally, in this plot, it considered that the packet correction technique has a correction capacity of just one bit, which is the worst case. As a consequence, observe that, as the packet size increases, the $\mathbb{E}\{\alpha\}$ results increase, since bigger packets are more likely to contain erroneous bits above the correction capacity of the proposed protocol. Moreover, it is considered the use of the AF scheme for all cases except case #2 in which it is considered the DF scheme. AF and DF are relaying schemes used at the physical layer level. When the AF scheme is considered, in case node R receives a corrupted packet from node S due to the PER_{SR}, the erroneous bits of this packet are forwarded by node R to node D in the cooperative retransmission. Otherwise, when the DF scheme is considered, in case node R receives a corrupted packet from node S due to the PER_{SR}, this packet is corrected before the retransmission and, as a consequence, node R does not forward erroneous bits to node D. In this last case, only the PER_{RD} may corrupt a packet retransmitted by node R.

Table 5: List of cases of study analyzed in Figure 24.

Case #1	without cooperation
Case #2	cooperation with DF scheme
Case #3	cooperation with AF scheme
Case #4	cooperation with AF scheme and $P_{corr} = 0.25$
Case #5	cooperation with AF scheme and $P_{corr} = 0.50$
Case #6	cooperation with AF scheme and $P_{corr} = 0.75$
Case #7	cooperation with AF scheme and $P_{corr} = 1$

.

Note that the case #1 does not consider cooperative MAC protocols, but it considers the use of the packet correction technique from the EPLC-CMAC protocol. In this case, $\mathbb{E}\{\alpha\}$ results are of 0.03, 0.38, 0.80 and 0.94, respectively. On the other hand, cases from #2 to #7 consider the use of both cooperative protocol and packet correction technique of EPLC-CMAC protocol under different circumstances. In order to analyze in which circumstances the use of the cooperative MAC protocol from EPLC-CMAC enhances its packet correction technique results, the case #1 results are considered as thresholds represented by dashed lines for each packet size. In other words, if a $\mathbb{E}\{\alpha\}$ result from a given packet size of a given case from #2 to #7 is above its correspondent threshold from case #1, it means that the use of the cooperative MAC protocol is not recommended.

In this regard, in case #2, the use of the cooperative MAC protocol benefits the packet correction technique, since the $\mathbb{E}\{\alpha\}$ results of each packet size are below their correspondent thresholds. In case #3, the use of the cooperative MAC protocol also benefits the packet correction technique regardless of the packet size. Cases #4 to #7 differs from case #3 by considering a correlation probability (P_{corr}) between the packets received by node R and by node D during the transmission from node S. It means that, in cases #4 to #7, these packets may have erroneous bits in the same binary position. This correlation may occur because the packet received by nodes R and D is transmitted by node S during the same time-slot and, as a consequence, with very similar channel conditions. In case this correlation occurs, the $\mathbb{E}\{\alpha\}$ result is high because the bitwise

XOR operation is not able to detect erroneous bits when two bits are wrong in the same binary position of the packets under the bitwise XOR operation. However, note that, even in case #7, the $\mathbb{E}\{\alpha\}$ value does not reach 1, because the erroneous bits of PKT_{rs} may be affected by the PER_{RD} and, as a consequence, lose its erroneous bits that were in the same binary position of the ones in PKT_{ds}. In terms of the cooperation efficacy to achieve low α, note that, in cases #4 and #5, the use of the cooperative MAC protocol is not suitable for small packets of 40 B since their $\mathbb{E}\{\alpha\}$ is above its correspondent threshold. In case #6, $\mathbb{E}\{\alpha\}$ values of packets with the sizes of 40 B and 250 B are also above the threshold. In the case #7, the use of the cooperative MAC protocol does not benefit the packet correction technique from EPLC-CMAC protocol in any of the analyzed packets sizes. Observe that smaller packets (e.g., 40 B and 250 B) are more sensible to the correlation probability. It is due to the fact that for longer packets (e.g., 750 B and 1500 B), most of the $\mathbb{E}\{\alpha\}$ results are related with the correction capacity of the packet correction algorithm. In other words, a packet with the size of 1500 B is more prone to have more erroneous bits than the correction capacity, which leads to a packet correction failure regardless of any correlation probability and, also, regardless of the use of the cooperative MAC protocol.

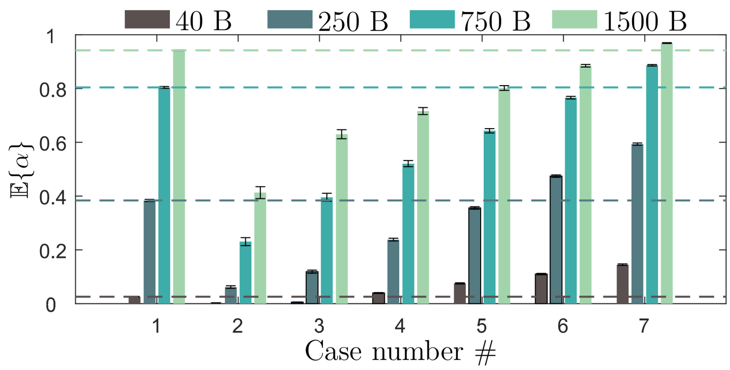
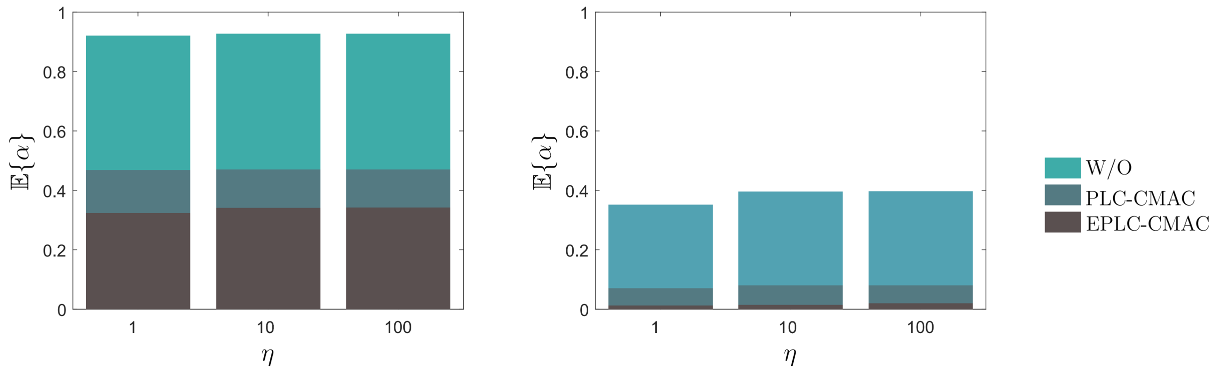


Figure 24: Mean packet loss ratio results in seven different cases of study.

Lastly, but not the least, Figure 25 shows the influence of the impulsive noise over the $\mathbb{E}\{\alpha\}$ results for an in-home PLC system employing the EPLC-CMAC protocol with a packet correction capacity of just one bit, the PLC-CMAC protocol or an in-home PLC system without neither the cooperative protocol nor the packet correction technique (W/O). These results are related to packets with the size of 500 B. The x-axis is the ratio in which BER values augment during the impulsive noise occurrence. Therefore, the first bar shows the $\mathbb{E}\{\alpha\}$ results when the impulsive noise does not influence BER values, which is the best case. Note that the $\mathbb{E}\{\alpha\}$ results show a low increment as η increases. Additionally, even in the worst case, the EPLC-CMAC protocol achieves the best results. In fact, in the TDMA-OFDM scheme, even when η is of 10^2, the $\mathbb{E}\{\alpha\}$ results are of 0.34, 0.47 and 0.93, respectively, for the in-home PLC system employing the EPLC-CMAC protocol, the PLC-CMAC protocol and the PLC system without neither the cooperative protocol nor the packet correction technique (see Figure 25.a). In the *OFDMA* scheme, the EPLC-CMAC protocol is capable of almost eliminating the α regardless of the adopted BER augment ratio (see Figure 25.b). It is observed that the presence of the impulsive noise, with the $t_{arr,r}$, $t_{arr,s}$ and the $t_{arr,s}$ described in Section 4.1.2, has low influence in the $\mathbb{E}\{\alpha\}$ of the studied scenarios. Furthermore, the existence of bursts of erroneous bits has low influence on the proposed protocol results. In fact, as the $\mathbb{E}\{\alpha\}$ of the proposed protocol is being analyzed when its correction capacity is of just one bit, the presence of more than one erroneous bit, consecutive or not, may cause a packet correction failure.



(a) TDMA-OFDM scheme. (b) OFDMA scheme.

Figure 25: Mean packet loss ratio for each BER augmentation ratio (η) associated with the impulsive noise occurrences.

4.5 SUMMARY

The main contributions of the present chapter are summarized as follows:

- It was outlined a new protocol, named as EPLC-CMAC, that uses system nodes as relays adaptively, according to their idleness or busyness, to assist the data communication between source and destination nodes. Additionally, the proposed protocol makes use of a bitwise XOR operation-based error detection technique and of a BFS algorithm to correct erroneous bits in corrupted packets.

- The proposed protocol limitations were identified and discussed. Furthermore, its failure probabilities were presented.

- Numerical results showed that the use of the EPLC-CMAC protocol becomes more relevant in situations in which the packet loss ratio is high, because, in this case, the packet correction technique is more requested. Moreover, performance improvements yielded by the proposed protocol depend upon the size of the packet. In addition, a performance comparison between OFDM and OFDMA schemes in all analyzed scenarios showed that the former yields lower performance gains than the latter.

5 AN ENHANCED COOPERATIVE MAC PROTOCOL FOR HYBRID PLC-WIRELESS SYSTEMS

PLC networks easily interconnect devices that are already plugged in power outlets. On the other hand, wireless networks offer interconnectivity among mobile devices. Recently, it has been recognized that both wireless and PLC networks can be seen as complementary technologies for providing the required flexibility and reliability for data communication [28, 283], since no single solution fits all scenarios [148].

However, there are several challenges related to the joint use of PLC and wireless networks. Regarding only PLC, it was mentioned in previous chapters that the dynamic of loads, the presence of high-power impulsive noises, the use of electromagnetically unshielded cables and the increasing signal attenuation as the frequency or distance increase [60, 239, 240] often degrade the performance of data communication system operating over electric power grids. On the other hand, the signal fading [232], the random behavior of wireless channels and the existing interferences [234,236] often degrade the performance of wireless data communication systems. In order to deal with these problems, it is common to find, in the literature, contributions addressing data communication reliability by introducing improvements at the physical layer level [74, 80, 236].

In this context, the joint use of PLC and wireless technologies as an hybrid communication system is an alternative to improve the data communication reliability and performance. A first discussion about such hybrid communication was held in [284]. This work showed that PLC may improve the signal quality in locations in which the indoor Wi-Fi coverage is not available or may not be possible. Later, in [285], authors used PLC as a flexible way to enhance wireless data communication, through cooperative relaying protocols, without additional wiring. In [79], authors analyzed a hybrid PLC-wireless relaying system that improves capacity and reliability of data networks for assisting the IoT deployment. This improved reliability offered by hybrid PLC-wireless systems in comparison with non-hybrid systems can be obtained even if the former system loses a data communication link or a node communication interface [78]. Moreover, [286–289] investigated, at the physical layer level, the diversity attained with hybrid PLC-wireless systems in order to improve data communication performance and reliability.

In summary, in the literature, it is common to find research efforts to maximize the diversity offered by hybrid PLC-wireless systems to increase data rate or reliability by building and modifying blocks of the physical layer of a data communication scheme. Another research direction is to assume that the physical layer is a black-box and, as a consequence, enhancements are introduced at the link layer. It opens the opportunity for improving hybrid PLC-wireless systems without the necessity of designing new physical layer techniques. In other words, this research direction can result in procedures and algorithms that can be implemented in standardized technologies with modifications only at the link layer level.

In this sense, the present chapter introduces EHCMAC, a new enhanced cooperative medium access control protocol. EHCMAC protocol takes advantage of the existing diversity, at the link layer level, among the bit streams received by an in-home PLC-wireless system for improving the reliability between source and destination nodes in a single relay model. More precisely, EHCMAC protocol makes use of system nodes as relays adaptively, according to their availability, to assist the end-to-end data communication between source and destination nodes. In addition, based on the generic approach from Chapter 3, the adoption of simple a packet correction technique, at the link layer, allows the proposed protocol to recover erroneous packets avoiding retransmissions and packet losses. After unsuccessful transmissions, the proposed protocol tries to correct corrupted packets, at the link layer, before issuing retransmission requests. In case this correction fails, the EHCMAC protocol exploits relay availability for retransmitting packets and, when the relay assistance is not enough to ensure successful retransmission, EHCMAC protocol applies a second packet correction attempt at the link layer to improve data communication reliability.

In sum, the major contributions, in the present chapter, are as follows:

- The proposal of EHCMAC protocol, a new MAC protocol that efficiently merges a cooperative protocol and a packet correction technique, at the link layer level, for improving the reliability of hybrid PLC-wireless systems.
- A detailed discussion of the EHCMAC protocol by scrutinizing its limitations regarding the use of an error correction technique based on the MV algorithm or on the BFS algorithm together with an error detection technique based on bitwise XOR operations.
- A comparative performance analyses of a hybrid PLC-wireless system that uses the proposed protocol (EHCMAC) against a hybrid PLC-wireless system that uses only a cooperative MAC protocol or only a packet correction technique, separately, and a hybrid PLC-wireless system without any enhancement at the link layer level.

In this sense, this chapter is organized as follows: Section 5.1 addresses assumptions, definitions and the studied scenario related to the present proposal. Section 5.2 describes the proposed protocol. Section 5.3 focuses on relevant information about the proposed protocol limitations and their probabilities. Section 5.4 presents simulation methodologies and performance analyses. Finally, Section 5.5 provides a summary of the present chapter.

5.1 SYSTEM MODEL

In the present work, it is considered a cooperative in-home hybrid PLC-wireless system, at the link layer level, using, but not limited to, the single relay channel model shown in Figure 26. Note that, in this figure, letters S, R and D denote source, relay, and destination nodes, respectively. Additionally, the Y-shaped lines above each node represent antennas, the continuous lines represent PLC channels and the dashed lines represent wireless channels. In this scenario, there are six links: source-destination PLC (SD$_P$) and wireless (SD$_W$), source-relay PLC (SR$_P$) and wireless (SR$_W$), relay-destination PLC (RD$_P$) and wireless (RD$_W$). It is assumed that each link has a BER, at the link layer, named as BER_k, where $k \in \{SD_P, SR_P, RD_P, SD_W, SR_W, RD_W\}$. Finally, it is assumed that the node R position is equidistant from nodes S and D, since it is the most appropriate scenario for relay-oriented MAC protocols, as shown in [69,77,276]. In [28,77] and under the physical layer perspective authors analyze a similar hybrid PLC-wireless system regarding distinct relative relay positions and, also, they present a system model for the physical layer.

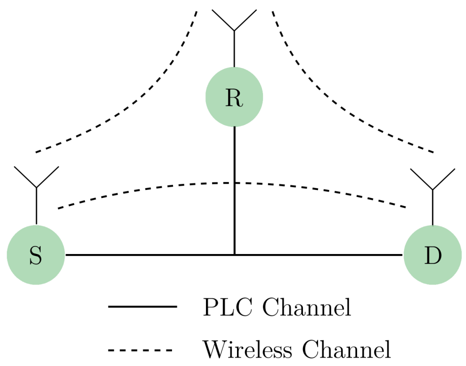


Figure 26: In-home single relay scenario.

In such hybrid PLC-wireless system showed in Figure 26, each packet transmission is performed in parallel through the PLC and wireless channels. For instance, when the node S transmits a packet, two copies of this packet are sent through the PLC channel and the wireless channel, respectively, and received by nodes R and D. Thus, each copy of the transmitted packet faces distinct channel degradation conditions, which can be exploited to increase data communication reliability at physical and link layers. Note that the focus of this hybrid PLC-wireless system is on the data communication reliability. More specifically, in such system, the PLC may assist the wireless portion in case of interferences or obstructions that attenuate the wireless communication [232, 234, 236]. On the other hand, the wireless communication may assist the PLC portion, for instance, when impulsive noises, impedance mismatch or even a cable rupture affect the communication over the electric power grid [241]. However, in spite of the diversity offered by this hybrid PLC-wireless system, techniques at the physical layer level may not be enough to ensure a reliable data communication between nodes S and D. In this case, it is appealing to investigate and propose techniques at the link layer level in order to improve this reliability without the need for changes at the physical layer.

In terms of channel assignment, it is considered a TDMA scheme in which each node has two time-slots (see Figure 27). The former time-slot corresponds to a SP, which is used for exchanging control messages, while the latter corresponds to a DP, which is applied for performing packets transmissions and receptions. It is assumed that time-slot sizes are big enough for transmitting packets with up to 100 B (bytes), during SP and up to 500 B during DP. Additionally, physical blocks with a body size of 500 B are considered to envelope packets from the link layer, which is similar to the physical block size described in [53]. Moreover, it is assumed that the control messages (e.g, ARQ messages) are error-free. Furthermore, it is assumed that each node has a reception buffer big enough so that no buffer problems occur. Finally, it is assumed that each frame is synchronized so that each node accesses the PLC and the wireless media at the same time.

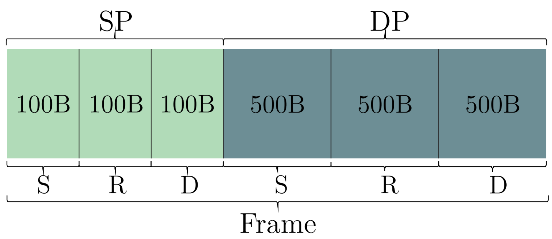


Figure 27: The TDMA scheme frame structure.

In terms of the physical layer, the use of the OFDM scheme is assumed. Additionally, the FEC scheme at the physical layer of the considered digital data communication system work together with an interleaving technique [53, 290], which is responsible for shuffling bits within each individual OFDM symbols and also spreading the bits over consecutive OFDM symbols. Based on these assumptions, correlated bit error bursts caused by the presence of impulsive noise in PLC channels as well as bit error bursts from any other sources in both PLC and wireless channels are spread over multiple OFDM symbols at the physical layer, which causes the remaining bit errors at the link layer to be virtually uncorrelated [291].

5.2 THE EHCMAC PROTOCOL

The EHCMAC protocol can be divided into three distinct processes: transmission, retransmission and correction. The transmission process is performed through the link SD. In case of a NACK from a transmission, a first attempt of packet correction occurs by using the correction process. If the correction process fails, the retransmission process starts. The retransmission process is performed through the link SD or though the links SR and RD, in case a cooperative retransmission occurs. After a NACK from a retransmission, the correction process is requested as a second attempt to correct the corrupted packet. In this section, it is provided a detailed description of each of these processes.

5.2.1 Transmission Process

Figure 28 shows the flowchart of the transmission process at the link layer perspective. Note that this process starts when node S transmits a PKT to node D, which is also received by node R. Thus, both nodes R and D has two copies of the PKT stored in their reception buffers, one from the PLC channel and another from the wireless channel. In case node D received at least one correct copy of the transmitted PKT, from any of its communication channels, it sends an ACK message to node S, which is also received by node R. As a consequence, nodes R and D clear the copies of the transmitted PKT from their buffers and node S is able to send a new PKT during its next time-slot. Otherwise, in case of node D did not receive any correct copy of the transmitted PKT, it activates the packet correction process. If the correction succeeds, node D sends an ACK message and nodes R and D clear the copies of the transmitted PKT from their buffers. On the other hand, if the correction fails, node D sends a NACK message asking for a retransmission process.

5.2.2 Retransmission Process

Figure 29 shows the flowchart of the retransmission process at the link layer perspective. This process starts when nodes S and R receive the NACK message from node D. In this case, if node R has at least one correct copy of the transmitted PKT stored in its buffer, it is possible to perform a cooperative retransmission. Thus, in case node R is idle (it does not have packets for transmission during its next time-slot), it sends a WTC message to node S offering its own time-slot for carrying out the cooperative communication at the link layer, which is similar to [85].

When node R is not idle to offer its own time-slot for the PKT retransmission, the EHCMAC protocol operates regardless of the relay idleness by performing cooperation during node S time-slot. In other words, node R will use the next node S time-slot for retransmitting the packet. Observe that, regardless of the relay node idleness, the proposed protocol does not add messages overhead during DP. In fact, the retransmission process uses a node R idle time-slot or a node S time-slot that was already reserved for PKT retransmission.

In case node R does not have any correct copy of the transmitted PKT stored in its buffer, it activates the packet correction process. If the correction succeeds, node R performs the aforementioned cooperative retransmission at the link layer. Otherwise, it sends a ITC message to node S, which informs that node S itself will have to perform

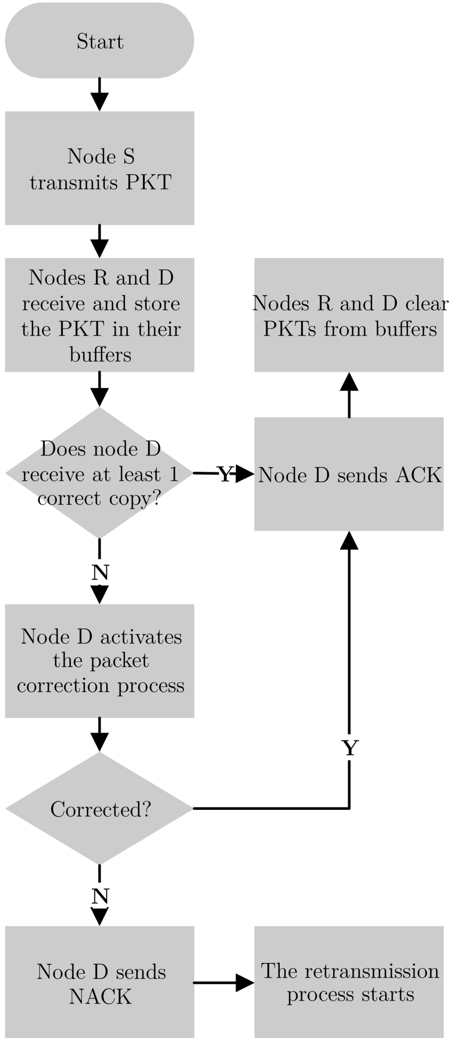


Figure 28: Transmission process of the EHCMAC protocol based on TDMA-OFDM scheme.

the retransmission without cooperation at the link layer. Figure 30 shows the messages exchanging before the PKT retransmission. Note that the WTC and ITC messages are the only control messages overhead added by this protocol.

After the retransmission process is finished, node D have four copies of the transmitted PKT in its reception buffer (i.e., two copies from the transmission and two copies from the retransmission over PLC and wireless channels of the single-relay hybrid PLC-wireless scenario). In case node D receives at least one correct copy of the transmitted PKT, it sends an ACK message. However, if all copies of the transmitted PKT in node D buffer are corrupted, it activates the packet correction process. Finally, regardless of the correction failure or success, nodes R and D discard the copies of the transmitted PKT from their buffers and node S sends a new PKT during its next time-slot. It is due to the fact that EHCMAC protocol considers only one retransmission attempt. If it fails and the transmitted PKT is not corrected, there is a PKT drop.

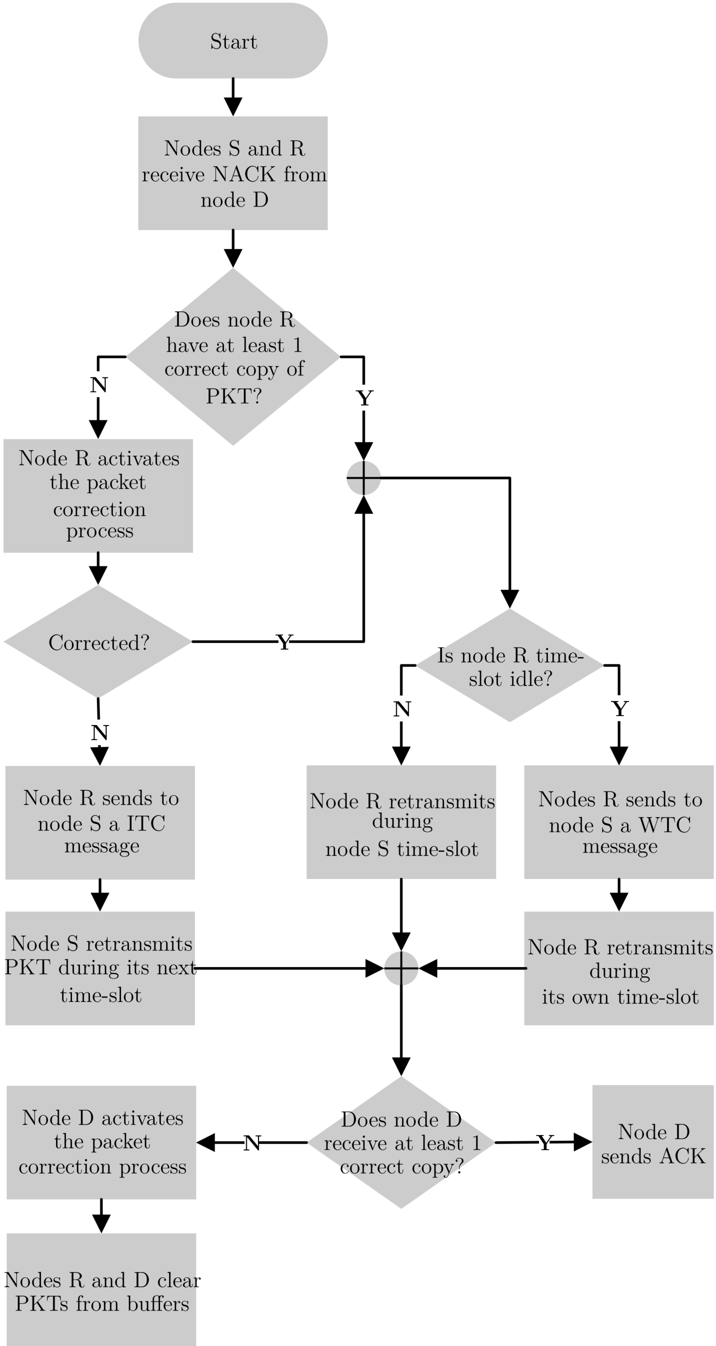


Figure 29: Retransmission process of the EHCMAC protocol based on TDMA-OFDM scheme.

5.2.3 Correction Process

Figure 31 shows the flowchart of the packet correction process. It is important to emphasize that this correction process is applied at the link layer level and, thus, it can be used regardless of the physical layer. In other words, the proposed packet correction attempt at the link layer level is an additional step in order to improve the reliability of the data communication. In this process, if the reception buffer has more than two corrupted copies of the transmitted PKT, then the MV algorithm is applied in order to

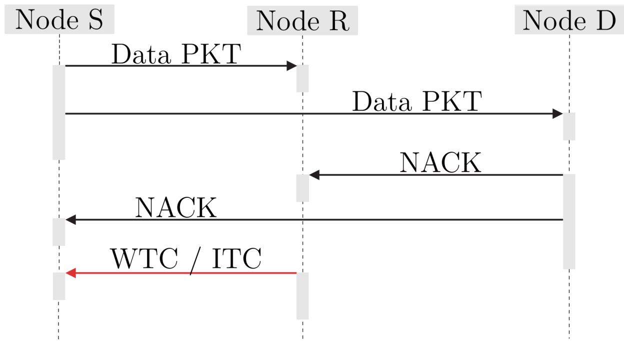


Figure 30: Messages exchanging before retransmission

correct the erroneous bits. Figure 32 shows an example of this algorithm. In this figure, PKT represents the correct bit sequence of the transmitted packet, PKT_P and PKT_W represents PKTs received from PLC and wireless channels, respectively, PKT_q is the result of the correction attempt, Tx and Rx indicate if the transmitted PKT was received from a transmission or from a retransmission process, in this order. Note that, when a given binary position of each copy of the transmitted PKT has different binary values (see the rectangles in Figure 32), the value that is present in the majority of the copies is considered as the correct value. After this PKT correction attempt, a CRC is applied in order to verify the packet correctness.

Despite the simplicity of the MV algorithm, it may fail when there is a tie between zeros and ones in the same binary position of each copy of the transmitted PKT. A tie situation may occur when there is an even number of copies of the transmitted PKT in the reception buffer. In addition, note that, when there are just two copies of the transmitted PKT, a tie is more likely to occur and, as a consequence, the MV algorithm is not recommended. Furthermore, this algorithm also fails when the majority of the copies of the PKT has an erroneous bit in a given binary position. In case of MV failure or if there are only two corrupted copies of the transmitted PKT in the reception buffer, the packet correction process uses a packet combining technique in order to detect the binary position of erroneous bits as shown in Figure 33. This packet combining technique is a simple bitwise XOR operation between the most recent two copies of the transmitted PKT from a reception buffer. In the example shown in Figure 33, there are three erroneous bits (see the bits inside the rectangles), which are detected by applying bitwise XOR operation between bits located at the same binary position ($PKT_{q_i} = PKT_{P_i} \oplus PKT_{W_i}$, $i = 1, 2, ..., N$) of the packets ($PKT_P \in \{0,1\}^N$ and $PKT_W \in \{0,1\}^N$, where $\oplus$ denotes a bitwise XOR and i denotes the i-th bit of packets PKT_P and PKT_W, which have the length of N bits). After finding these bits, it is applied a BFS algorithm, which tries all possible combinations of bits for correcting the transmitted PKT (for this example, there are $2^3 - 2$ possibilities considering the three erroneous bits). A CRC is applied after each try in order to verify the successful correction of the transmitted PKT. Note, in Figure 31,

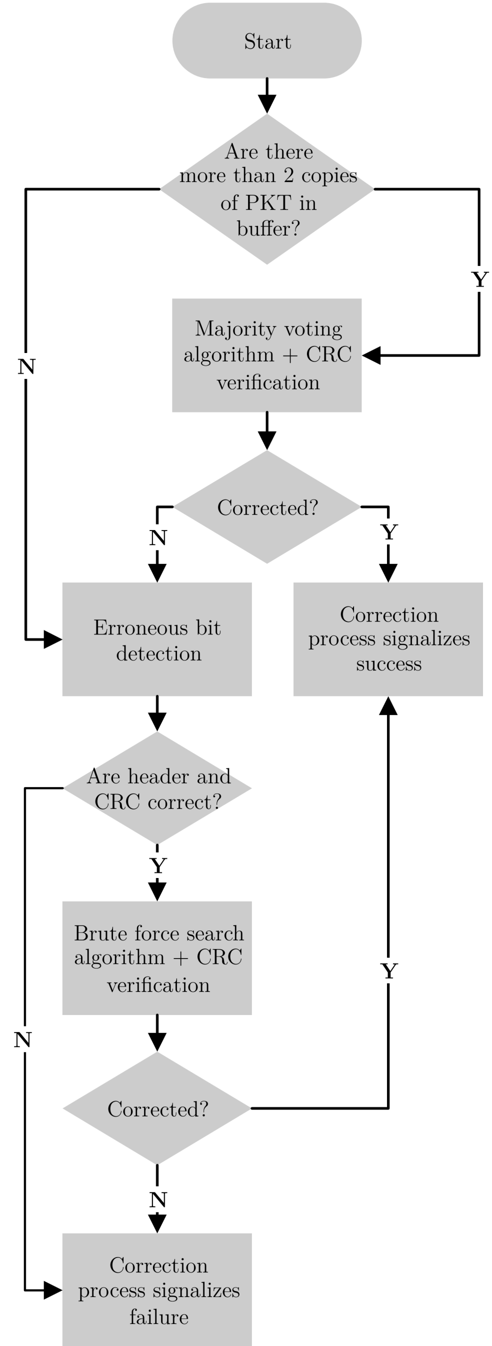


Figure 31: Packet correction process of the EHCMAC protocol.

that there is a verification of the packet header and CRC integrity before using the BFS algorithm. If these fields are not correct, the error correction will not be reliable since the packet header carries its sender and receiver addresses and a corrupted CRC cannot be used to verify packet integrity. Thus, in this case, if the bitwise XOR detects at least one erroneous bit within these fields, the packet correction process is aborted.

Observe that the use of the bitwise XOR together with the BFS algorithm has two flaws. The first flaw is related to the exponential complexity of the BFS algorithm as the number of erroneous bits per packet increases. In the worst case, the BFS algorithm

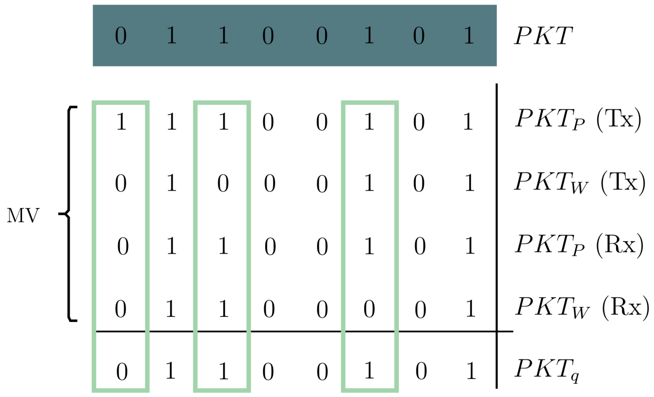


Figure 32: An example of the use of the majority voting algorithm.

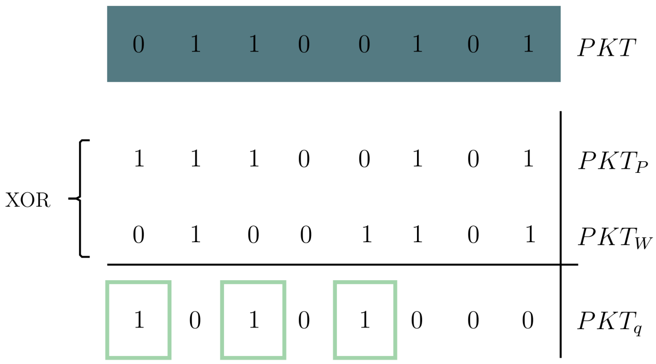


Figure 33: An example of the detection of erroneous bits at node D.

will execute $2^\gamma - 2$ correction attempts in which $\gamma \in \mathbb{N}^*$ is the number of erroneous bits detected by the bitwise XOR operation. The latter flaw occurs when the bit error detection fails. It may happen if one or more bits are erroneous in the same position among the XORed packets. This situation cannot be handled by the proposed protocol, but it can be avoided by considering [269].

The present chapter focuses on the single-relay channel model, but the proposed protocol is not limited to this model. The main requirement to extend the proposed protocol to a multi-hop scenario is the choice of the best relay node. In this sense, in [70, 282], authors investigate interesting approaches for choosing the best relay. In other words, the proposed packet correction technique can be applied, at the link layer level, to any other model in which at least two copies of the transmitted packet by node S are available in node D.

5.3 PACKET CORRECTION ALGORITHM FAILURE PROBABILITIES

In this section, failure probabilities related to the erroneous bit detection through the bitwise XOR operation and to the packet correction through BFS or MV algorithm are discussed. In this sense, it is presented a set of equations in which ϵ_{PTx} and ϵ_{WTx} are equal to the BER associated with PLC and wireless channels, respectively, during the transmission process. More specifically, $\epsilon_{PTx} = BER_{SD_P}$ and $\epsilon_{WTx} = BER_{SD_W}$. On the other hand, ϵ_{PRx} and ϵ_{WRx} are equal to the BER associated with PLC and wireless channels, respectively, during the retransmission process. In other words, $\epsilon_{PRx} = BER_{SD_P}$ and $\epsilon_{WTx} = BER_{SD_W}$, when the retransmission occurs without cooperation, or $\epsilon_{PRx} = BER_{SRD_P}$ and $\epsilon_{WRx} = BER_{SRD_W}$, otherwise, in which BER_{SRD} is the total BER associated with links SR and RD.

5.3.1 XOR + Brute Force Search

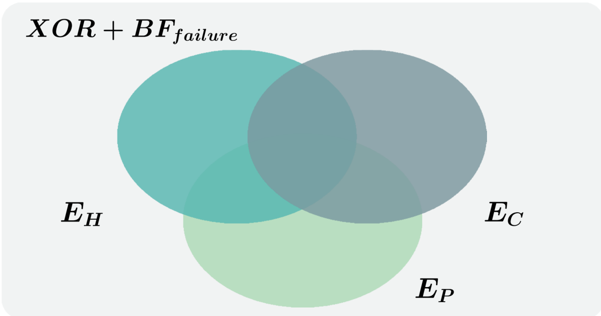


Figure 34: XOR + Brute Force events that lead to a correction failure.

As previously showed in Figure 31, the combination XOR+BFS (i.e., the erroneous bit detection through the bitwise XOR operation and the packet correction through the BFS algorithm) fails under certain circumstances. More specifically, there are three distinct events that lead to a XOR+BFS failure. First, the event E_H = {there is at least one erroneous bit within the header field of one or both packets under the bitwise XOR operation} occurs with the probability $\mathbb{P}(E_H)$, which is given by

$$\mathbb{P}(E_H) = \sum_{i=1}^{N_h} \binom{N_h}{i} \epsilon_{PTx}^{i} (1 - \epsilon_{PTx})^{N_h - i} + \sum_{i=1}^{N_h} \binom{N_h}{i} \epsilon_{WTx}^{i} (1 - \epsilon_{WTx})^{N_h - i} - \sum_{i=1}^{N_h} \sum_{j=1}^{N_h} \binom{N_h}{i} \binom{N_h}{j} \epsilon_{PTx}^{i} \epsilon_{WTx}^{j} (1 - \epsilon_{PTx})^{N_h - i} (1 - \epsilon_{WTx})^{N_h - j}, \quad (5.1)$$

in which N_h is the packet header length in terms of number of bits. Note that, in equation (5.1), $\mathbb{P}(E_H)$ is related to the combination XOR+BFS applied as an attempt to correct a packet after an unsuccessful transmission. Analogously, when the combination XOR+BFS is applied after unsuccessful retransmissions $\mathbb{P}(E_H)$ is given by replacing ϵ_{PTx} and ϵ_{WTx} by ϵ_{PRx} and ϵ_{WRx}, respectively, in the same equation.

Second, the event E_C = {there is at least one erroneous bit within the packet CRC field of one or both packets under the bitwise XOR operation} occurs with the probability $\mathbb{P}(E_C)$, which $\mathbb{P}(E_C)$ is given analogously to the equation (5.1), when N_h is replaced by the packet CRC length in terms of number of bits (N_c).

Finally, the event E_P = {there is at least one undetectable erroneous bit within the packet payload} occurs with the probability $\mathbb{P}(E_P)$, which is given by

$$\mathbb{P}(E_P) = \sum_{i=1}^{N_p} \binom{N_p}{i} \epsilon_{XOR}^{i} (1 - \epsilon_{XOR})^{N_p - i}, \tag{5.2}$$

in which N_p is the packet payload length in terms of number of bits and $\epsilon_{XOR} = \epsilon_{PTx}\epsilon_{WTx}$, after unsuccessful transmissions, is the probability in which erroneous bits are in the same binary position between the packets under the bitwise XOR operation and, as a consequence, these erroneous bits are undetectable. Analogously, $\epsilon_{XOR} = \epsilon_{PRx}\epsilon_{WRx}$ when the combination XOR+BFS is applied after unsuccessful retransmissions.

The events E_H and E_C occur after a bitwise XOR operation, when at least an erroneous bit is detected within the header or the CRC fields, respectively. On the other hand, E_P occurs when there is at least one erroneous bit in the same binary position between the packets under the bitwise XOR operation.

Figure 34 shows how these events are related to each other. In this regard, the total failure probability of the combination XOR+BFS is given by

$$\begin{aligned} \mathbb{P}(E_{XBF}) = \mathbb{P}(E_H) + \mathbb{P}(E_C) + \mathbb{P}(E_P) - \\ \mathbb{P}(E_H)\mathbb{P}(E_C) - \mathbb{P}(E_C)\mathbb{P}(E_P) - \\ \mathbb{P}(E_H)\mathbb{P}(E_P) + \mathbb{P}(E_H)\mathbb{P}(E_C)\mathbb{P}(E_P). \end{aligned} \tag{5.3}$$

5.3.2 Majority Voting

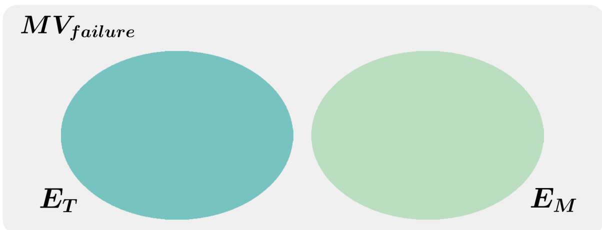


Figure 35: Majority voting events that lead to a correction failure

The MV algorithm fails due to two distinct and mutually exclusive events. The event E_T = {there is a tie of votes at the i-th binary position among the packets under MV} occurs with the probability $\mathbb{P}(E_T)$, which is given by

$$\begin{aligned} \mathbb{P}(E_T) = (1 - \epsilon_{PTx})(1 - \epsilon_{PRx})\epsilon_{WTx}\epsilon_{WRx} + \\ (1 - \epsilon_{PTx})(1 - \epsilon_{WTx})\epsilon_{PRx}\epsilon_{WRx} + \\ (1 - \epsilon_{PTx})(1 - \epsilon_{WRx})\epsilon_{PRx}\epsilon_{WTx} + \\ (1 - \epsilon_{PRx})(1 - \epsilon_{WTx})\epsilon_{PTx}\epsilon_{WRx} + \\ (1 - \epsilon_{PRx})(1 - \epsilon_{WRx})\epsilon_{PTx}\epsilon_{WTx} + \\ (1 - \epsilon_{WTx})(1 - \epsilon_{WRx})\epsilon_{PTx}\epsilon_{PRx}. \end{aligned} \tag{5.4}$$

Note that, as the MV algorithm is using four corrupted copies of a given packet, E_T occurs when a combination of two of these four copies have erroneous bits in a given binary position. It is important to emphasize that E_T does not occur when the number of corrupted copies of the transmitted packet within the reception buffer is odd. In this regard, a viable option to avoid E_T in the hybrid PLC-wireless system presented in Section 5.1, is to perform a packet retransmission by using only the PLC or the wireless channel. In this case, if this retransmission fails, the reception buffer will have only three corrupted copies of the transmitted packet (two from the transmission over the PLC "and" the wireless channels and one from the retransmission over the PLC "or" the wireless channel). Another interesting option to avoid E_T, when the number of corrupted copies of the transmitted packet is even, is to ignore the worst copy under the MV algorithm, which can be identified according to SNR estimates performed at the receiver [265, 266]. However, in the present chapter, it is considered the full hybrid PLC-wireless scenario in which both PLC and wireless systems are always used in parallel and all corrupted copies are used by the MV algorithm. Thus, E_T may occur with the probability $P(E_T)$ given by the equation (5.4).

In addition, the event $E_M = \{$the majority of the votes at the i-th binary position among the packets under MV are wrong$\}$ occurs with the probability $\mathbb{P}(E_M)$, which is given by

$$\begin{aligned}\mathbb{P}(E_M) = &(1-\epsilon_{PTx})\epsilon_{PRx}\epsilon_{WTx}\epsilon_{WRx}+\\ &(1-\epsilon_{PRx})\epsilon_{PTx}\epsilon_{WTx}\epsilon_{WRx}+\\ &(1-\epsilon_{WTx})\epsilon_{PTx}\epsilon_{PRx}\epsilon_{WRx}+\\ &(1-\epsilon_{WRx})\epsilon_{PTx}\epsilon_{PRx}\epsilon_{WTx}+\\ &\epsilon_{PTx}\epsilon_{PRx}\epsilon_{WTx}\epsilon_{WRx}.\end{aligned} \tag{5.5}$$

Note that, as the MV algorithm is using four corrupted copies of a given packet, E_M occurs when a combination of three of these four copies or all four copies have erroneous bits in a given binary position.

Figure 35 shows how the events E_T and E_M are related to each other. Observe that E_T and E_M may occur in one or more binary positions of the packets under the MV algorithm. In this regard, the probability in which the MV does not succeed correcting corrupted packets is given by

$$\begin{aligned}\mathbb{P}(E_{MV}) = 0.5&\sum_{i=1}^{N}\binom{N}{i}\mathbb{P}(E_T)^i(1-\mathbb{P}(E_T))^{N-i}+\\ &\sum_{i=1}^{N}\binom{N}{i}\mathbb{P}(E_M)^i(1-\mathbb{P}(E_M))^{N-i},\end{aligned} \tag{5.6}$$

in which $N = N_h + N_p$ is the size of the copies of the packet in terms of number of bits.

Note that the first portion of equation (5.6) if multiplied by 0.5, because, when a tie occurs, the MV algorithm fails with the probability of 50%.

5.3.3 Transmission and Retransmission Correction Failure

After the transmission process, in case node D receives two corrupted copies of a given packet, it tries to detect the erroneous bits from these copies with the bitwise XOR operation and correct them by using the BFS algorithm. If this correction attempt fails with the probability $\mathbb{P}_{Tx_{failure}}$, node D will need to ask a retransmission to node S. This probability is given by

$$\mathbb{P}_{Tx_{failure}} = \mathbb{P}(E_{XBF}). \tag{5.7}$$

On the other hand, after an unsuccessful retransmission process, node D has four corrupted copies of the packet within its buffer. In this case, it is able to apply the MV algorithm as a first correction attempt. If this attempt fails, the combination XOR+BFS is used in the two corrupted copies received during the retransmission process. The packet is discarded when both correction attempts fail with the probability $\mathbb{P}_{Rx_{failure}}$, which is given by

$$\mathbb{P}_{Rx_{failure}} = \mathbb{P}(E_{MV})\mathbb{P}(E_{XBF}). \tag{5.8}$$

In summary, note that only the combination XOR+BFS is applied in order to correct a corrupted packet after an unsuccessful transmission. Otherwise, both MV and the combination XOR+BFS are applied after a NACK from a retransmission. If both algorithms fail, the packet is discarded, since the proposed protocol considers only one retransmission attempt. Therefore, $\mathbb{P}_{Rx_{failure}}$ also represents the probability of a packet loss occurrence after an unsuccessful retransmission.

5.4 PERFORMANCE ANALYSES

In this section, it is analyzed the proposed protocol impact on the data communication reliability of the hybrid PLC-wireless system described in Section 5.1. In this sense, theoretical results are presented by using the equations (5.1)-(5.8) and numerical results are obtained according to the simulation methodology described in Section 5.4.1.

5.4.1 Simulation Methodology

In order to analyze the performance of the proposed protocol in terms of data communication reliability, two parameters are used: the retransmission ratio and the packet loss ratio. Furthermore, for the sake of simplicity, the results related to these parameters consider packets with the size of 500 B. Therefore, it is assumed that a full packet transmission is performed during a single time-slot according to the MAC frame characteristics described in Section 5.1.

The retransmission ratio α_{Tx} refers to the ratio in which the packet correction technique fails to correct packets from unsuccessful transmission processes. In order to obtain this result, packet transmissions from node S to node D are simulated under different BER values at the link layer, from 10^{-5} to 10^{-2}. After each unsuccessful transmission, the combination XOR+BFS is applied between the two corrupted packets stored in node D buffer (one packet received through the PLC channel and one through the wireless channel), trying to correct them and, as a consequence, to avoid retransmission requests. Thus, α_{Tx} is given by

$$\alpha_{Tx} = \frac{Q_{TxCF}}{Q_{PTx}}, \tag{5.9}$$

in which Q_{TxCF} is the number of failures to correct packets from unsuccessful transmissions and Q_{PTx} is the total number of packets sent from node S to node D. When the proposed packet correction is not considered, α_{Tx} is calculated by replacing, in equation (5.9), Q_{TxCF} by the number of unsuccessful transmissions. Theoretically, α_{Tx} is evaluated through the equation 5.7.

Differently from α_{Tx}, the packet loss ratio α refers to the ratio in which the packet correction technique fails to correct packets from unsuccessful retransmission processes. In order to obtain α results, packet retransmissions are simulated under different BER values ranging from 10^{-5} to 10^{-2} under the use or not of the proposed protocol. After each unsuccessful retransmission, the MV algorithm is used among the four corrupted copies of the packet stored in node D buffer (two from the transmission process and two from the retransmission process over the PLC and the wireless channels). After each MV correction failure, the combination XOR+BFS is applied between the two packets received from the retransmission process as the last attempt to avoid the packet loss. In this context, α is given by

$$\alpha = \frac{Q_{RxCF}}{Q_{PRx}}, \tag{5.10}$$

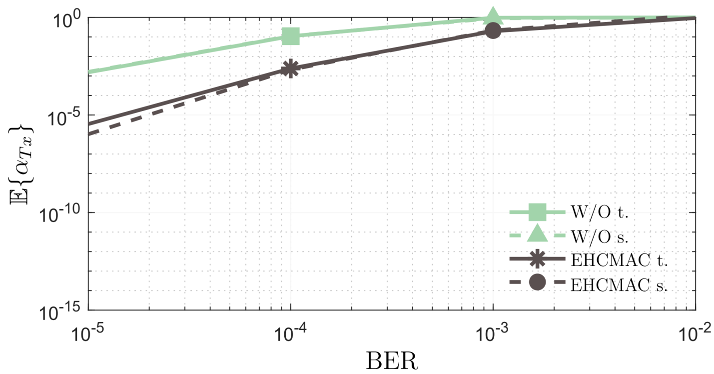
in which Q_{RxCF} is the number of failures to correct packets from unsuccessful retransmissions and Q_{PRx} is the number of retransmissions. When the proposed packet correction is not considered, α is calculated by replacing, in equation (5.10), Q_{RxCF} by the number of unsuccessful retransmissions. Theoretically, α is evaluated through the equation 5.8. Finally, Table 6 summarizes the details of the simulations performed in the MATLAB software.

Table 6: Simulation parameters.

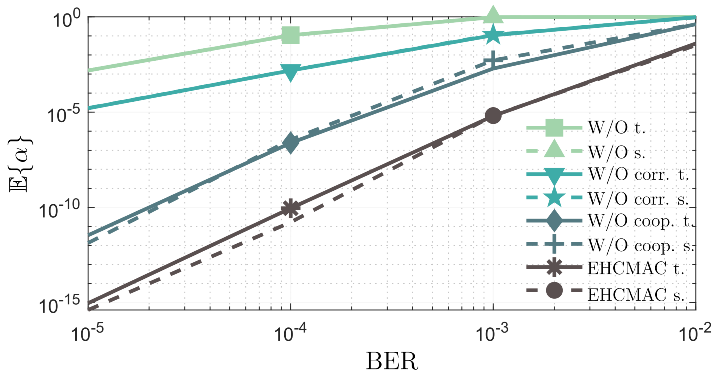
Parameter	**Value**
BER	10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}
Packet size (bytes)	500
Number of transmissions	10^6
Number of simulations	100

5.4.2 Results

Figure 36 shows the expected values of α_{Tx} ($\mathbb{E}\{\alpha_{Tx}\}$) and α ($\mathbb{E}\{\alpha\}$) for the hybrid PLC-wireless system described in Section 5.1 under different circumstances. More specifically, Figure 36.a shows $\mathbb{E}\{\alpha_{Tx}\}$ results for different BER values in a hybrid PLC-wireless system without any cooperative MAC protocol nor packet correction technique at the link layer level, named as W/O, and in a hybrid PLC-wireless system that considers the proposed protocol, EHCMAC. In this plot, continuous and dashed lines refer to theoretical (t.) and simulated (s.) results, respectively. Note that, EHCMAC protocol outperforms W/O for all the analyzed BER at the link layer, presenting lower $\mathbb{E}\{\alpha_{Tx}\}$ results. Moreover, note that, the difference between EHCMAC protocol and W/O $\mathbb{E}\{\alpha_{Tx}\}$ results tend to increase as the BER decreases. In fact, for the highest analyzed BER of 10^{-2}, $\mathbb{E}\{\alpha_{Tx}\}$ are of $10^{-0.03}$ and 10^{0} for the EHCHMAC and the W/O, respectively. This is as small difference when compared to results related to a BER of 10^{-5}, in which the former $\mathbb{E}\{\alpha_{Tx}\}$ is of $10^{-5.46}$ while the latter is of $10^{-2.79}$. Hence, through these curves behavior it is possible to observe that, as the BER decreases, EHCMAC protocol tends to 0 faster than W/O. In summary, this plot shows that EHCMAC protocol, in comparison to W/O, may substantially reduce the need for retransmissions in the studied hybrid PLC-wireless system.



(a)



(b)

Figure 36: $\mathbb{E}\{\alpha_{Tx}\}$ and $\mathbb{E}\{\alpha\}$ results for each BER value.

In terms of packet loss ratio, Figure 36.b shows $\mathbb{E}\{\alpha\}$ results for different BER values at the link layer, in four different scenarios. The first one is a hybrid PLC-wireless system considering the aforementioned W/O. The second one is a hybrid PLC-wireless system that considers only the proposed cooperative MAC protocol without the proposed packet correction technique, named as W/O corr.. The third one is a hybrid PLC-wireless system that considers only the proposed packet correction technique without the use of the proposed cooperative MAC protocol, named as W/O coop. Lastly, the fourth one is a hybrid PLC-wireless system that considers the proposed protocol, EHCMAC. In this plot, continuous and dashed lines refer to theoretical and simulated results, respectively. Note that the EHCMAC protocol achieves the lowest $\mathbb{E}\{\alpha\}$ result even for the highest analyzed BER value. In fact, when the BER is of 10^{-2} the theoretical $\mathbb{E}\{\alpha\}$ is of 10^{0}, $10^{-0.02}$, $10^{-0.36}$ and $10^{-1.23}$ for the W/O, the W/O corr., the W/O coop. and the EHCMAC protocol, respectively. Additionally, it is possible to note through results related to the BER ranging from 10^{-5} to 10^{-3}, that the W/O corr. itself is capable of substantially reducing the $\mathbb{E}\{\alpha\}$ in comparison to W/O. It is due to the diversity offered by relayed retransmissions in which node R is closer to node D than node S. However, for all analyzed BER values, the lowest $\mathbb{E}\{\alpha\}$ results are related to the W/O coop. and to the EHCMAC protocol, respectively. It shows that the use of the proposed packet correction technique may improve the data communication reliability even when used without the proposed cooperative MAC protocol, but when they are used together on the EHCMAC protocol, the lowest $\mathbb{E}\{\alpha\}$ results are achieved. For instance, theoretical $\mathbb{E}\{\alpha\}$ results are of $10^{-2.81}$, $10^{-4.80}$, $10^{-11.38}$ and $10^{-14.78}$ for the W/O, the W/O corr., the W/O coop. and the EHCMAC protocol, respectively, when the BER is of 10^{-5}. Furthermore, observe that, similarly to Figure 36.a, as the BER decreases, the $\mathbb{E}\{\alpha\}$ curve related to the EHCMAC protocol tends to 0 faster than the others. Therefore, the EHCMAC protocol is an appealing solution for improving the data communication reliability, reducing the packet loss ratio over the studied hybrid PLC-wireless system.

Overall, it is important to emphasize that the proposed protocol uses a BFS algorithm for correcting corrupted packets from unsuccessful transmissions and from unsuccessful retransmissions when the MV fails. The use of this algorithm, in the worst case, requires $2^{\gamma} - 2$ iterations in order to try all possible combinations to correct corrupted packets, as mentioned in Section 5.2. In other words, as the the number of detected erroneous bits γ increases, the number of iterations of the BFS algorithm, in the worst case, increases exponentially. Figure 37 shows the expected value of γ ($\mathbb{E}\{\gamma\}$) when the packet size and the BER at the link layer vary. Note that, as expected, as the BER decreases, $\mathbb{E}\{\gamma\}$ considerably decreases. For instance, a packet with the size of 100 B has the $\mathbb{E}\{\gamma\}$ of 1.6 for the BER of 10^{-3} and of 16 for the BER of 10^{-2}. Additionally, as the packet size decreases, its associated $\mathbb{E}\{\gamma\}$ also decreases. For example, $\mathbb{E}\{\gamma\}$ is of 2.4 and of 0.16 for packets with the size of 1500 B and 100 B, respectively, when the BER is of

10^{-4}. Although these results are expected, they show that, as the packet size decreases or the BER decreases, less iterations will be necessary for the BFS algorithm to correct corrupted packets in the worst case. In fact, for the BER of 10^{-5}, $\mathbb{E}\{\gamma\}$ is of 0.24 for packets with the size of 1500 bytes and of 0.02 for packets with the size of 100 B. Thus, the use o the BFS with a small number of iterations, depending on the BER at the link layer of the studied hybrid PLC-wireless system, may lead to appealing $\mathbb{E}\{\alpha_{Tx}\}$ and $\mathbb{E}\{\alpha\}$ results in comparison to other protocols (W/O, W/O corr. and W/O coop.).

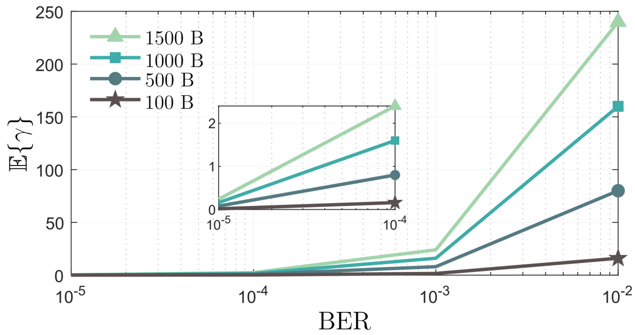


Figure 37: Mean number of erroneous bits detected per packet when the BER and the packet size vary.

5.5 SUMMARY

The main contributions of the present chapter are summarized as follows:

- It was proposed a new MAC protocol, named as EHCMAC, which efficiently merges a cooperative protocol and a packet correction technique, at the link layer level, for improving the reliability of hybrid PLC-wireless systems.
- The failure probabilities related to the packet correction technique considered by the proposed protocol were presented.
- Performance analyses were performed by considering theoretical and simulated results of a hybrid PLC-wireless system that uses the proposed protocol (EHCMAC) against a hybrid PLC-wireless system that uses only a cooperative MAC protocol or only a packet correction technique, separately, and a hybrid PLC-wireless system without any enhancement at the link layer level. Numerical results showed that the use of the proposed protocol is capable of reducing the need for retransmissions and the packet loss ratio of the analyzed hybrid PLC-wireless system.

6 CONCLUSIONS

The present thesis focused on proposals for improving the data communication reliability at the link layer level. In this sense, it was surveyed the state of the art related to PLC MAC protocols with the objective of improving knowledge bases necessary for the identification of open research issues. Then, it was proposed a generic approach that considers the use of a packet correction technique at the link layer level for improving the data communication reliability. Based on this generic approach, novel MAC protocols for improving data communication reliability over PLC systems and hybrid PLC-wireless systems were proposed.

Chapter 2 surveyed the state of the art and analyzed recent research on PLC systems from a MAC sublayer perspective. More specifically, it was provided an overview of existing PLC MAC research results and an organization of current PLC MAC protocols in terms of type of protocols, applications, and main research focus. This organization showed that the majority of PLC MAC protocols are proposed for broadband PLC systems. Additionally, it also showed that the majority of PLC MAC protocols are based on contention-based MAC methods such as the CSMA/CA and their research focus are predominantly on throughput improvements. Moreover, it was identified that multimedia and smart grid are the most common targets of these protocols. Furthermore, the survey presents modern PLC technologies and standards, highlighting their MAC sublayer characteristics. In this regard, it was showed that the main PLC standards consider the use of the CSMA/CA as the main MAC method, which is suitable for reducing energy consumption and improving resource sharing in applications such as smart things. However, some broadband PLC standards also consider the optional use of the TDMA, in general, for multimedia and real time applications in which a predictable round-trip time is desirable for strict QoS requirements. In sequel, it was provided a detailed comparative analysis of PLC MAC protocols in the context of current and emerging PLC applications. Lastly, but not the least, this chapter discussed several challenging research topics associated with the MAC sublayer in order to improve PLC systems. The presented open research issues may motivate the development of new research to improve data communication technologies in IoT, Smart Things, multimedia, in-vehicle applications and new ones, such as the Industry 4.0.

Chapter 3 identified a problem when preexistent physical layer techniques and protocols are not enough to ensure the data communication reliability. In such case, retransmission requests and even packet losses may occur. In order to mitigate this problem, this chapter introduced a generic approach in which an extra step of packet correction is performed at the link layer level so that the legacy of standardized physical layers may be preserved. This approach is based on simple redundancy-free algorithms, such as the majority voting and the brute force search together with bitwise XOR operations, which use corrupted copies of the transmitted packet in order to detect and correct their erroneous bits. In this sense, packet correction limitations related to the use of such algorithms are exposed and evaluated. More specifically, the bitwise XOR operation fails to detect erroneous bits that are in the same binary position between the XORed packets. Additionally, the brute force search algorithm is not able to correct corrupted packets with corrupted header or CRC fields, because the former has important information such as source and destination addresses and the latter is used to verify the packet correctness. Moreover, the brute force search algorithm needs only two corrupted copies of the transmitted packet in order to perform a correction attempt, however, its execution may require a number of iterations that exponentially increase as the number of erroneous bits to be corrected increases. For this reason, the use of the majority voting algorithm is considered when at least three copies of the corrupted packet are available. Nevertheless, this algorithm may fail if there is a tie of erroneous and correct bit values in a given binary position when the number of corrupted copies of the transmitted packet is even. Furthermore, this algorithm also fails when the majority of the bit values in a given binary position is erroneous. In order to verify the impact of the proposed approach on the data communication reliability, distinct cases of study are presented in the next chapters.

Chapter 4 detailed the proposed EPLC-CMAC: an enhanced cooperative MAC protocol for in-home broadband PLC systems. The proposed protocol uses system nodes as relays adaptively, according to their idleness or busyness, to assist the data communication between source and destination nodes. More specifically, it allows the retransmission of packets through different paths by exploiting the existing diversity in the single-relay channel model for improving data communication through in-home PLC systems. In addition, based on the generic approach introduced in chapter 3, the proposed protocol makes use of a bitwise XOR operation-based error detection technique and of a brute force search algorithm to correct erroneous bits in corrupted packets. Furthermore, this chapter discussed several relevant information related to the use of the EPLC-CMAC protocol, such as possible correction capacity limitations. Moreover, in this chapter, it was evaluated the performance of the proposed protocol and, based on numerical results, it was shown that the use of the EPLC-CMAC protocol becomes more relevant in situations in which the packet loss ratio is high, because, in this case, the packet correction technique is more requested. Furthermore, a performance comparison between OFDM and OFDMA schemes in all analyzed scenarios showed that the former yields lower performance gains than the latter.

Chapter 5 outlined an enhanced hybrid cooperative MAC protocol for in-home broadband hybrid PLC-wireless systems, named as EHCMAC. After unsuccessful packet transmissions, the proposed protocol makes use of a bitwise XOR operation-based error detection technique and of a brute force search algorithm to correct erroneous bits in packets, at the link layer, in order to reduce the need for packet retransmissions. In case this first packet correction attempt fails, a retransmission request is issued. After unsuccessful retransmissions, the proposed protocol uses a majority voting algorithm to correct erroneous bits, at the link layer. If the majority voting algorithm fails, the proposed protocol applies the bitwise XOR based detection and the brute force search between the retransmitted packets as the last packet correction attempt. Theoretical and numerical results showed that the use of the proposed protocol may remarkably increase the reliability of in-home hybrid PLC-wireless systems. More specifically, as the bit error rate at the link layer decreases, the expected value of packet loss ratio and the need for retransmissions tend to zero faster when the proposed protocol is considered. It is due to the fact that packets with erroneous bits can be recovered, at the link layer level, instead of being simply retransmitted or discarded.

6.1 FUTURE WORKS

Future efforts can be addressed in order to:

- To investigate multihop scenarios with data acquired from measurement campaigns.
- To investigate the best implementation approaches regarding proposed protocols in digital communication systems.
- To implement and test proposed protocols in digital communication systems.

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Appendix A – Publications

The list of papers accepted for publication, published and under review during the doctoral period are as follows:

- R. M. Oliveira, M. S. Facina, M. V. Ribeiro, and A. B. Vieira, “Performance evaluation of in-home broadband PLC systems using a cooperative MAC protocol,” *Computer Networks*, vol. 95, pp. 62-76, Dec. 2015
- R. M. Oliveira, A. B. Vieira, H. A. Latchman, and M. V. Ribeiro, “Medium access control protocols for power line communication: A survey,” *IEEE Communications Surveys & Tutorials*, vol. 21, pp. 920-939, Aug. 2018.
- R. M. Oliveira, A. B. Vieira and M. V. Ribeiro, “EPLC-CMAC: An Enhanced Cooperative MAC Protocol for Broadband PLC Systems,” *Computer Networks*, vol. 153, pp. 11-22, Jan. 2019.
- R. M. Oliveira, L. G. de Oliveira, A. B. Vieira and M. V. Ribeiro, “An Enhanced Cooperative MAC Protocol for Hybrid PLC-Wireless Systems,” *Journal of Network and Computer Applications*, Jan. 2019, under review.

The list of conference papers published during the doctoral period are as follows:

- R. M. Oliveira, M. S. Facina, M. V. Ribeiro, and A. B. Vieira, “Um Protocolo MAC de Cooperação para Redes PLC,” in *Proc. Simpósio Brasileiro de Redes de Computadores e Sistemas Distribuídos*, 2015.
- L. M. F. Silveira, R. M. Oliveira, L. F. M. Vieira, M. A. M. Vieira, A. B. Vieira, and M. V. Ribeiro, “CodePLC: A network coding MAC protocol for power line communication,” in *Proc. IEEE Local Computer Networks*, Nov. 2016, pp. 643-646.
- L. M. F. Silveira, R. M. Oliveira, M. V. Ribeiro, M. A. M. Vieira, L. F. M. Vieira and A. B. Vieira, “Um Protocolo de Acesso ao Meio com Network Coding em Ambiente PLC,” in *Proc. Simpósio Brasileiro de Redes de Computadores e Sistemas Distribuídos*, 2016.

The follow patents were deposited during the doctoral period:

- R. M. Oliveira, A. B. Vieira and M. V. Ribeiro, “Processo de Detecção e Correção de Erros na Camada de Enlace de Sistemas de Comunicação de Dados,”, Brazil, Dec. 2018, under review.

- R. M. Oliveira, A. B. Vieira and M. V. Ribeiro, "Processo de Correção de Erros na Camada de Enlace de Sistemas Híbridos PLC-Wireless,", Brazil, Mar. 2019, under review.