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Medium Access Control Protocols for Power Line Communication: A Survey

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***Abstract*—In the literature, the majority of research efforts in power line communication (PLC) has been focused on the physical layer in order to deal with issues such as time varying behavior of loads in electric power systems, the presence of high power impulsive noise, the occurrence of impedance mismatching, widespread use of unshielded power cables and coupling losses. While some work has also been done on the PLC Medium access control (MAC) sublayer, there is scope for further research to address the novel demands associated with cyber physical systems that need to mitigate unfairness in resource sharing, collisions and starvation, among other issues which may degrade data communication quality. In this paper we provide a comprehensive survey regarding the state of the art of MAC protocols for 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, we present 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. Finally, we identify future trends within the scope of the MAC sublayer for PLC systems with a view to stimulating additional research efforts on PLC MAC design.**

***Index Terms*—Power line communication, medium access control, time division multiple access, carrier sense multiple access.**

I. INTRODUCTION

Power line communication (PLC) has been attracting worldwide attention due to its usefulness for smart grids, Internet of Things, multimedia, in-vehicle data communication, among other applications [1]. PLC technology requires less investment in additional telecommunication infrastructure, since it works over preexisting electric power system infrastructure. 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 [2], [3].

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The use of electric power grids as a telecommunication 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 [4]. 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 grids [5]–[7], smart home [8]–[10], in-vehicle data networks [11]–[13], high-speed network [14], home area network [15]–[17], smart metering [18], [19], multimedia and access data network [20]–[22].

Regardless of the applications, widely used PLC standards, such as HomePlug [23], IEEE 1901 [24], IEEE 1901.2 [25], ITU.T G.hn [26] and ITU-T G.hnem [27] focus their specifications on physical (PHY) 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 PHY 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 [28].

A. PLC PHY and MAC Research

Historically, PLC research efforts have been largely focused on the PHY 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 [29], [30]; remarkable signal attenuation when frequency and/or distance increase(s); impedance mismatching at the points of connection among power lines, loads and transceivers [31]; high power impulsive noises yielded by connecting and disconnecting loads, equipment and alternate current/direct current (AC/DC) converters [32]–[34]; electromagnetic interference due to the use of unshielded power lines and coupling problems [35], [36]); 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 [37]–[39]. For instance, [40], [41] and [42]–[44] proposed, respectively, cooperative protocols and resource allocation techniques to improve PLC system performance at the PHY layer to handle some of these issues. Moreover, [45]–[52] investigated hybrid data communication media, which involves PLC and wireless channels, aiming to

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improve performance (data-rate and reliability) at the PHY layer.

On the other hand, relevant data communication features are related to the medium access control (MAC) sublayer. For example, unfairness of resource allocation [53], starvation [54], collisions [21] and channel access delay [55] 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 [56]. In fact, MAC protocols are capable of reinforcing PLC system reliability and performance [57], [58] and guaranteeing quality of service (QoS) [59].

Despite the variety of existing MAC protocols and their relevance for PLC systems, there is a lack of comprehensive analyses and discussion, in the literature, driving attention to PLC systems within the MAC sublayer perspective. Various surveys about PLC focus on subjects related to the PHY layer [60]–[62], 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 [63]–[65] 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.

B. Overview of Contributions

This paper offers a comprehensive survey about the MAC sublayer for PLC systems because it is one of the most important component 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 [66], [67] related to internet of things (IoT), smart things, multimedia and in-vehicle applications. In order to establish a systematic presentation of several aspects related to PLC MAC protocols, this work deals with the following contributions:

- An organization of PLC MAC protocols into contention-free, contention based, and hybrid. Moreover, we classify these protocols in terms of applications and main research focus.
- A description of the main PLC standards and their MAC sublayer characteristics. Additionally, we analyze PLC applications, 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 we believe can offer some guidances 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.

The remainder of this paper is organized as follows: Section II focuses on the suggested organization of PLC MAC protocols. Section III addresses PLC standards from a MAC sublayer perspective. Sections IV, V and VI focus on Smart Things, multimedia and in-vehicular applications, respectively, while Section VII addresses future trends and potential research issues. Finally, Section VIII provides some concluding remarks.

II. PLC MAC Protocols Organization

In this section, we organize PLC MAC protocols from the literature into well-known subgroups (i.e., frequency bandwidth, channel assignment, medium access methods, application and main research focus). In this regard, we aim at offering an index for the readers in order to facilitate the study of the state of the art.

MAC protocols are often associated with MAC methods to perform several functionalities, such as multiple access, resource sharing and traffic control [28]. According to [37], 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.

A. Organization based on Frequency Bands

Based on PLC MAC protocols characteristics [14] and on well-established terminologies in the PLC community, we can offer the organization presented in Figure 1. In this figure, we organize, initially, MAC protocols into NB (low-bit-rate) and BB (high-bit-rate) PLC technologies [121] due to the fact that both of them demand distinct solutions of their MAC sublayers in terms of requirements of the associate 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 [25]), lower bit-rates (i.e., kbps), and can be used in short and long distance applications (up to a hundred of Km [122]). On the other hand, broadband PLC (BPLC) works at higher frequencies (e.g., from 1.7 MHz up to 100 MHz [24]), 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, [70] 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 [122], have been inspiring the use of NB-PLC in smart grids applications [68], such as smart meters [19], smart homes [71] and in-vehicle [13].

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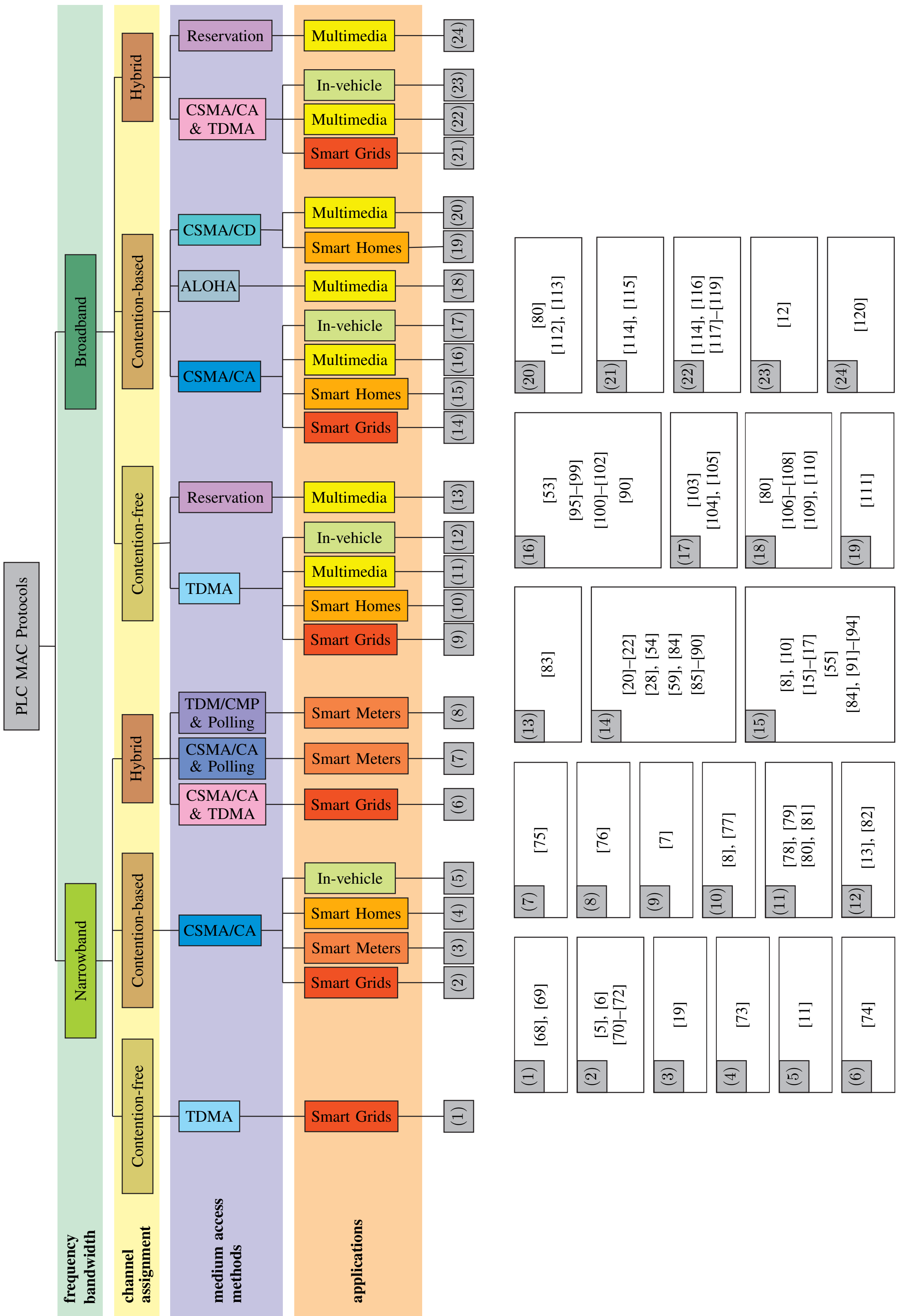

Figure 1: The organization of PLC MAC protocols.

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B. Organization based on Channel Assignment and MAC Methods

Regarding each application, attentions can be given to the channel assignment methods, which highlight MAC protocol research when the applications are grouped in typical types (i.e. Smart Things, multimedia and in-vehicle). The following statements are valuable regarding contention-free, contention-based or hybrid MAC protocols for NB and BB applications:

- Contention-free protocols, such as the ones based on TDMA access method [68], [78], [79] and on polling-based protocols [75], [76]. 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) [70], [73], [84], carrier sense multiple access/collision detection (CSMA/CD) [112], [113] and on ALOHA protocols [106]–[108]. 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 [123] and in IEEE 1901 [24]. 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 [76], 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.

C. 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 our 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 and 4, 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 taken into account.

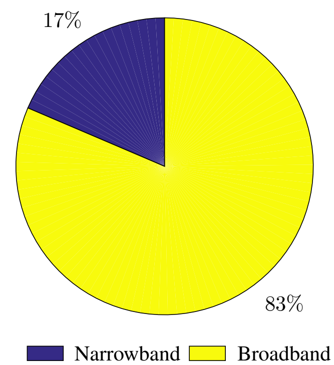

Figure 2: Frequency Bands of PLC MAC protocols.

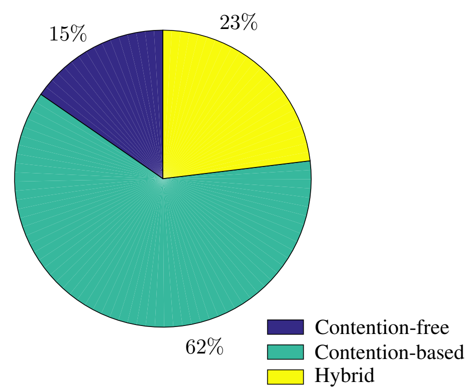

Figure 3: Types of MAC protocols in narrowband PLC systems.

For the CSMA/CA, collisions and starvation are common problems. The former occur when more than one user attempts to access the medium at the same time. We discuss several works which focus on building and modifying backoff procedures to mitigate this problem. 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

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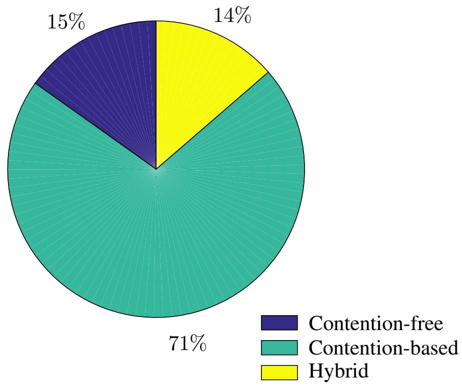

Figure 4: Types of MAC protocols in broadband PLC systems.

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 being considered for designing the MAC sublayer of PLC systems [120], [124], [125]. These kind of protocols 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.

D. Discussion about the Research Focus

Another perspective to organize PLC MAC protocols is in terms of their applications, as we suggest 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, we evaluated the percentages presented in Figure 5, which show that multimedia is the most common application using these protocols.

Lastly, Table I 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 we present in Figure 6, 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 which 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, we found a work that analyzes buffer management and starvation in a priority-based scheme adopted in a contention-based MAC protocol.

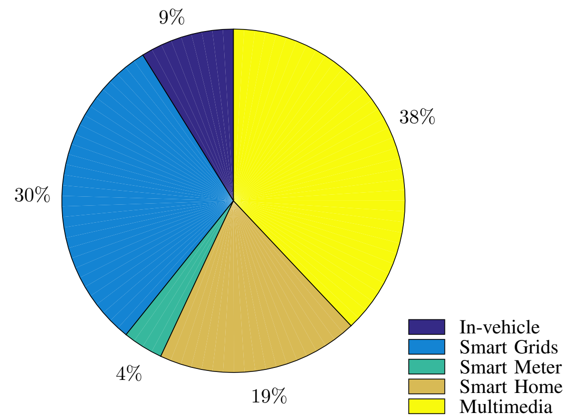

Figure 5: Main applications of PLC MAC protocols.

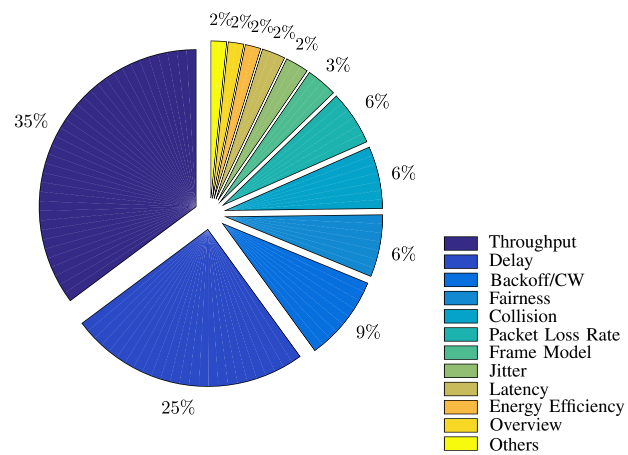

Figure 6: Main focus of PLC MAC protocols.

In the following sections, we use the aforementioned classifications to organize the state of the art. Furthermore, we discuss PLC Standards and MAC protocols within the scope of their applications.

III. MAC Protocols in PLC Standards and Technologies

In this section, we present the most common Standards in which PLC MAC protocols and technologies are based, highlighting their MAC sublayer characteristics.

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 and/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 [25], which involves players like G3-PLC

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

Research Focus	Related Works
Throughput	[5]–[8], [10], [11], [15]–[21], [68]–[70] [73], [74], [76], [79]–[81], [83], [84] [86]–[89], [91]–[94], [96], [97], [99]–[102] [106], [111]–[113], [115]–[118], [120], [126]
Delay	[5], [7], [11], [14], [16]–[20], [28] [59], [70], [74]–[76], [80], [81], [84], [85] [87], [105]–[110], [115]–[118], [120]
Backoff/CW	[21], [22], [55], [70], [74], [84] [90], [97], [98], [117], [127]
Fairness	[5], [15], [53], [70], [73], [93], [94], [126]
Collision	[11], [12], [74], [84], [94]–[96] [101]–[105]
Packet Loss Rate	[8], [19], [72], [80], [87], [95], [96]
Frame Model	[9], [77], [128]
Jitter	[10], [59], [85]
Latency	[10], [78]
Energy Efficiency	[13], [71], [82]
Overview	[114], [119]
Buffer Management	[54]
Starvation	[54]

Alliance [129]; ITU-T G.hnem [27]; PRIME [130], developed by the the PRIME Alliance [131].

Different from NB-PLC systems, BPLC systems [132] operate in a wider frequency bandwidth and, as a consequence, they achieve much higher bit-rates. Thus, applications such as multimedia [78], in-home internet service [16], indoor data network [114] and some smart grids applications [7] use BPLC systems.

In this context, in the year of 2001, the HomePlug Powerline Alliance released the HomePlug 1.0 Standard [23], 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 [123]. In the same year, a working group of IEEE initiated a a project aimed at the unification of power line technologies in a single standard named as IEEE 1901 [24], which addressed both in-home and access broadband applications [133], [134]. In 2006, ITU-T started the G.hn project [135] 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 [26].

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 [136] and Atmel [137] manufacture NB-PLC chipsets for smart things with support for G3-PLC, IEEE 1901.2 and PRIME standards; Maxim Integrated [138] commercializes NB-PLC chipsets compatible with IEEE 1901.2, ITU-T G.hnem, G3-PLC and PRIME standards; Qualcomm [139] manufactures BPLC chipsets for smart-things, multimedia and in-vehicle applications based on HomePlug standards and IEEE 1901; MegaChips [140] manufactures PLC chipsets for smart things applications fully compliant with HD-PLC; Panasonic [141] manufactures BPLC chipset for multimedia based on HD-PLC; Marvell [142] manufactures chipsets compatible with ITU-T G.hn for home broadband network connectivity.

The aforementioned PLC standards present PHY and link layers parameters and characteristics which 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 II and III 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 grids, smart meter and smart home) and in-vehicle data networks [6], [105]. On the other hand, there are BPLC standards which also consider the use of TDMA [143], in general, for multimedia and real time applications [13], [81]. In fact, the predictable round-trip time of the TDMA is desirable for applications with strict QoS requirements, as mentioned earlier. In sections IV, V and VI, we expand our discussions focusing on PLC MAC protocols within the scope of the main PLC applications.

Table II: NB-PLC standards.

Standard	MAC Method	Main applications
PRIME [130]	CSMA/CA	smart things
G3-PLC [144]	CSMA/CA	smart things, in-vehicular
IEEE 1901.2 [25]	CSMA/CA	smart things, in-vehicular
ITU-T G.hnem [27]	CSMA/CA	smart things, in-vehicular

Table III: BPLC standards.

Standard	MAC Method	Main applications
HomePlug 1.0 [23]	CSMA/CA	home area networks
HomePlug AV [123]	CSMA/CA, TDMA	multimedia
HomePlug AV2 [145]	CSMA/CA, TDMA	multimedia
HomePlug GP [146]	CSMA/CA	smart things, in-vehicular, multimedia
IEEE 1901 [24]	CSMA/CA[1], TDMA	smart things, in-vehicular, multimedia
HD-PLC [147]	CSMA/CA, TDMA	smart home
ITU-T G.hn [26]	CSMA/CA, TDMA	smart things in-vehicular
ITU-T G.hn-MIMO [148]	CSMA/CA, TDMA	home networks

IV. 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 [151]. The basic idea of this concept is the interconnection of a variety of objects (e.g., electric and electronic devices) [152], which create scenarios of pervasive technology, such as smart cities, smart homes, smart grid,

[1]Recently, Vlachou et. al [149], [150] analyzed the IEEE 1901 Standard and proposed modifications to enhance its CSMA/CA performance when compared to its default configuration.

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, we discuss the MAC sublayer from the perspective of "smart things".

A. Smart Grid

Historically, the first PLC applications were related to load management, electricity meter reading and telephonic communications [4], [37]. 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 [153].

Smart grid are modern electric power systems which improve the efficiency and resilience of energy generation, transmission, delivery and consumption in terms of security, reliability and flexibility [154], [155]. 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 [156]. In the literature, there are interesting surveys regarding smart grid challenges, motivations and open issues [157]–[159]. Thus, in the present work, we focus on discussing PLC MAC protocols in the context of smart grid applications. Figure 7 shows the smart grid interconnecting smart applications and renewable energy sources.

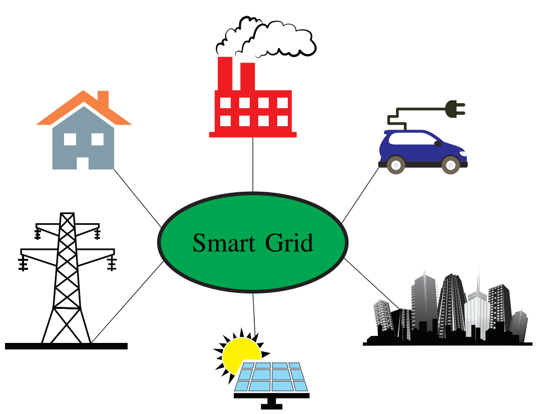

Figure 7: Smart Grid interconnecting industry, home, electric cars and renewable energy sources.

Overall, smart grid heavily rely on the use of pervasive telecommunication infrastructure. In this sense, [160] 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) [161] and can work as distributed sensing systems. Furthermore, [153] 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, [162] and [122] 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 [101], [102]. In the literature, there are authors who proposed the use of contention-free protocols instead of contention-based protocols in NB scenarios [68]. 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 [7]. 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, [6] 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 [96], 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, [6], [72] 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) [146] and IEEE 1901 [24]) uses CSMA/CA as their main MAC method. On the other hand, [8] 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 which use both TDMA and CSMA/CA were described in [74], [115]. More specifically, in [115], 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 which 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 [74], 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 [74], TDMA and CSMA/CA periods will always exist during every frame thus eliminating the required switching time associated with the approach in [115], 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 [98]–[100]. In this sense, [70] 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 [97] 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, [5] compared different backoff algorithms in terms of key performance parameters, such as goodput, fairness and collisions. In [95], 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 which 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 [71]. Essentially, they outlined the adaptation of the IEEE 802.15.4 Standard [163] (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.

B. Smart Meters

Historically, automatic meter reading (AMR) and advanced metering infrastructure (AMI) are recognized as critical steps in the smart grid world [164]. 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 8). However, these monitoring functionalities can also create privacy problems, which are matters of concern in recent studies about the smart meter application [165], [166]. 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 which consider privacy issues is an important research topic. In this sense, [165] highlighted confidentiality, integrity, authenticity, non-repudiation and auditability as the main security requirements for privacy-preserving protocols. Moreover, in order to ensure billing privacy, [166] 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.

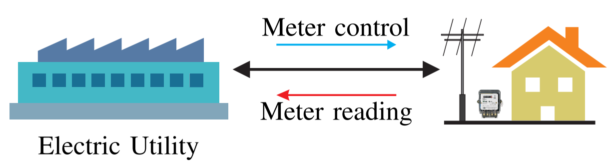

Figure 8: Smart meter basic operations

In the literature, we find several works that modify pre-existent PLC standards and protocols in order to improve meter reading performance. For instance, [19] verified the impact of the digital modulation scheme on the performance of the PRIME Standard [130] in a cross layer approach, which involved PHY 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 PHY 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 [53]. 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 [75], 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, [76] 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 [76], 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.

C. Smart Homes

Smart homes attracted researchers attention with the advent of IoT. For instance, [167] 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 9). 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 [92]. Additionally, [91] 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 9: 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 [168]. In this sense, [9] 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 [169], 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, [55] 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 [16], [17] which 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 orthogonal frequency division multiple access (OFDMA) scheme can reduce collision rate and, as a consequence, improve system throughput [15], [73], [93]. 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 [111]. For instance, [77] 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

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of network resource allow the elimination of idle time-slots by allocating network resources only for active users. Lastly, in [92], 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 which 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.

In the next section, we discuss PLC MAC protocols in the context of multimedia applications, a growing demand among household applications.

V. 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 [170]. Additionally, in [171], 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 [172].

The launch of the HomePlug AV Standard [123], [173] further motivated the use of multimedia applications based on PLC systems. The QoS requirements of these applications using this standard were presented in [119]. 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 [85]. 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 which 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, [59] offered a protocol which is activated when these QoS parameters start deteriorating. Essentially, [59] 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, [88], [89], [100] 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 orthogonal frequency division multiplexing (OFDM) scheme, such as the one in the HomePlug standards. Moreover, [88] 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 and/or backoff period of CSMA/CA from BPLC standards. For instance, [22], [90] 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, [22], [90] 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 [21], [126], 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 [86], 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 PHY layer was introduced in [86]. 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 which 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 [87]. It involves choosing which type of traffic will receive channel

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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 and/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, [20] analyzed CSMA/CA backoff period and proposed a simplified mathematical model taking into account 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 [54], 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, [80] 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 [113], the authors also show good results related to the use of CSMA/CD. However, collision detection requires a full duplex communication, because users which perform data communication need to sense the channel until the transmission ends. Thus, contention-based protocols which use CSMA/CD may adopt a multi-band OFDM (MOFDM) scheme with two sub-bands of frequency [112]. 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 [116], [117]. 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 which 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, [118] 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 which 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 [79]. For instance, a protocol based on the TDMA scheme in which the coordinator node chooses a set of nodes which can share the same time-slot was addressed in [81]. Results showed throughput improvement and delay reduction compared to traditional TDMA. Additionally, [78] analyzed the protocol based on TDMA proposed in the OPERA Standard [174]. In this protocol, the coordinator node sends a token to the node which 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, [174] 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 [28]. As an alternative, several researches supported the use of distributed protocols based on the ALOHA protocol [83], [107]–[110]. Nevertheless, in this case, it is important to consider collision avoidance strategies, because collision is one of the major ALOHA protocol drawbacks [175].

VI. 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 [176]. 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 [177], [178]. 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 [11].

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 [179]. Moreover, the weight reduction improves vehicle performance and increases its efficiency in terms of fuel consumption. Applications which 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 [180].

There are authors who defend the use of contention-based protocols for PLC in-vehicle applications. For instance, [11] 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, [105] 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, [103], [104] introduced a contention-based protocol for minimizing collisions in a BPLC in-car application. The authors outlined a modified CSMA/CA which 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, [13], [82] 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, we recommend the reading of [181], which presents an interesting purpose for time-slots allocation that could be adapted to in-vehicle applications.

Alternatively, [12] 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.

In the next section, we suggest some interesting research topics for investigation that are not well-addressed in the PLC scenario, but could yield interesting results.

VII. Future Trends

In this section, we aim to present open research topics which 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, we identify some application-oriented insights and open problems, which could be useful information for the PLC community. Then, we highlight PLC and wireless networks similarities in order to find interesting research topics yet little explored in the PLC scenario. Further, we present several open research issues and appealing suggestions for reliability improvement at the link layer level of PLC systems. Lastly, but not the least, we present promising resource sharing approaches which could be adapted for PLC systems.

A. Application-Oriented Insights and Open Issues

During the analysis of the main PLC applications, we have identified interesting open research issues which could be considered in future works. For instance, regarding the smart meter application, the development of MAC protocols considering potential privacy problems [165], [166] is an important research topic in order to avoid the misuse of the meter reading information. Regarding the smart home application, we emphasize that 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 [169]. Regarding the multimedia application, the vulnerability of PLC systems to denial-of-service attacks is a relevant issue yet little explored [54]. 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 [11], 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 [105]. In this context, the use of contention-free MAC protocols with a variable time-slot size [181] for optimizing the use of the network resources is a promising topic yet little explored for in-vehicle critical applications.

B. 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 [172]. 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

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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) [182]–[184] and non-orthogonal multiple access (NOMA) schemes [185], [186] 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.

C. 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 [187]. In this regard, cooperative communication at the link layer (e.g., cooperative MAC protocols) uses neighbor nodes as relays to intermediate data transmissions and/or retransmissions between a node source and a node destination [172]. For instance, [57] 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 [188].

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 [189]. The use of network coding can reduce data communication overhead and improve system performance [58] 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 node destination reception buffer and combined in order to find and, then, correct their erroneous bits [184]. In the literature, it is common to find hybrid ARQ techniques associated with chase combining [190] or incremental redundancy [191] 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, 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 [192] 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. For instance, Figure 10 shows cumulative distribution functions of packet loss ratios by considering packets of 500 Bytes in a PLC single-relay channel model. The dashed curves are associated with the numerical results which makes use of the OFDMA scheme at the physical layer, while the continuous curves refer to results associated with the use of the OFDM scheme at the physical layer. The first two legends of this plot refers to the curves related to the so-called enhanced PLC MAC protocol (EPLC-CMAC protocol), which uses packet correction and cooperation at the link layer. The third and fourth legends refer to results of the PLC-CMAC protocol [57], which considers only cooperation at the link layer. The last two legends refer to the curves related to a PLC system that does not use any cooperative protocol nor packet correction technique at the link layer. Note that the curves of EPLC-CMAC protocol show the lowest packet loss ratio results when compared to the others even when we consider that the correction of only for one erroneous bit per packet at the link layer. That is something that could be more investigated in order to introduce improvements at the link layer with minimal changes in the whole MAC protocol.

As an alternative to improve reliability of data communication, hybrid PLC-wireless scenarios can improve system diversity [45]–[49], [193]. In such scenarios, data communication is performed through PLC and wireless channels working in parallel. More specifically, after any transmission,

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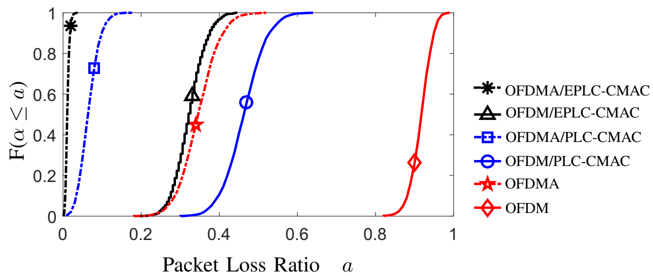

Figure 10: Packet loss ratio results considering the maximum correction of 1 bit per packet.

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, equipments 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) [194]. 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 being 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.

D. 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 [195]. 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 survey.

Additionally, we believe that the novel approach used in medium access related to 5G [196], [197] holds significant promise for the design of new generations of PLC systems. For instance, recent investigations on 5G have focused on NOMA schemes [185], [186], 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 [198], 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 [199]. 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 [200]. 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 [201], 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 [202] and the efficient utilization of the available spectrum based on the cognitive radio concepts [203], 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 [204], 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.

VIII. Conclusions

In this paper we have discussed MAC methods and MAC protocols within the scope of PLC applications and standards. In this sense, we have surveyed the state of the art and analyzed recent research on PLC systems from a MAC sublayer perspective. We focused on identifying and extending the basic knowledge that allows us to explore the state of the art and the challenges for improving the current PLC MAC protocols and/or developing novel ones.

We have brought to the readers' attention several research works on MAC contention-based and contention-free protocols which aim at improving the CSMA/CA and TDMA performances, respectively. Furthermore, we have pointed out that hybrid protocols are associated with trade-off among advantages of contention-based and of contention-free protocols. Moreover, we have emphasized that the suggested organizations of the works from the literature can guide researchers and practitioners interested in research activities related to PLC MAC protocols.

Finally, but not the least, we have discussed several challenging research topics associated with the MAC sublayer in order to improve PLC systems. The open research issues we have presented 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.

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