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Review

Strategies for Power Line Communications Smart Metering Network Deployment

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Abstract: Smart Grids are becoming a reality all over the world. Nowadays, the research efforts for the introduction and deployment of these grids are mainly focused on the development of the field of Smart Metering. This emerging application requires the use of technologies to access the significant number of points of supply (PoS) existing in the grid, covering the Low Voltage (LV) segment with the lowest possible costs. Power Line Communications (PLC) have been extensively used in electricity grids for a variety of purposes and, of late, have been the focus of renewed interest. PLC are really well suited for quick and inexpensive pervasive deployments. However, no LV grid is the same in any electricity company (utility), and the particularities of each grid evolution, architecture, circumstances and materials, makes it a challenge to deploy Smart Metering networks with PLC technologies, with the Smart Grid as an ultimate goal. This paper covers the evolution of Smart Metering networks, together with the evolution of PLC technologies until both worlds have converged to project PLC-enabled Smart Metering networks towards Smart Grid. This paper develops guidelines over a set of strategic aspects of PLC Smart Metering network deployment based on the knowledge gathered on real field; and introduces the future challenges of these networks in their evolution towards the Smart Grid.

Keywords: smart metering; smart grid; PLC; broadband (BB); narrowband (NB); ultra-narrowband (UNB); strategy; deployment; distribution grid

1. Introduction

The Smart Grid is recognized today as a revolutionary concept that, even with some of the problems associated to the lack of consensus over a unique and closed definition [1–8], is in the process of being implemented in many electricity grids all over the world. Within the aspects that may be highlighted as standing within the consensus of the utility community in the Smart Grid definition, we find the addition of recent advances of electronics, and information and communications technologies (ICTs) applied on the distribution grid electricity assets, to get a better energy supply based on remote monitoring and metering of the existing assets, a better adjustment between energy production and consumption, the optimization of operation reaction times, and the improvement in the grid technical losses. Smart Metering is the application that is experiencing greater support both from the industry and utilities, that find in the deployment of smart meters an opportunity to build the foundations for a larger scope Smart Grid, while obtaining some immediate advantages derived from the savings and commercial opportunities based on the real time access to customers' smart meters.

PLC is a telecommunications technology with a long history and tradition in electricity companies, with a wide scope of applications, varieties and implementations. The confluence of the Smart Metering and PLC technologies has been highlighted from the very first conception of PLC systems, and increasingly in the last decades. The projection of PLC into the Smart Grid is a matter that has been specifically addressed by [9], recognizing in PLC "*an excellent and mature technology that can support a wide variety of applications from the transmission side to the distribution side and also to and within the home*".

From a purely academic perspective, the evolution of the subjects focusing the attention of researchers on PLC has followed the historical path of industry interest (high voltage (HV)-lines propagation, metering and control, medium voltage (MV)-environment, broadband (BB) access, and in-home communications). Of late, Smart Grids have focused much of the attention of both industry and academic world, through an evolution in which Smart Metering has been the core of the interest.

The PLC literature is mainly composed of academic papers focused on low level specific details of PLC technology. Noise, channel characteristics, modulation schemes, MAC architectures, *etc.* (see reference [10]), are extensively covered by academic researchers. With all this information, PLC technology has managed to progress and evolve into different system specifications that have subsequently been applied on real field to provide real services.

However, the application of any PLC technology to the electricity grid is not straightforward. The so-called "PLC learning curve" might not be easy for an electricity company that needs to make use of PLC to deploy a service-oriented PLC system. Electricity grid specific details are not often found in the conventional scientific literature and even in the electricity industry related associations (e.g., [11]). Thus the deployment of PLC solutions is often a field in which utilities cannot be easily assisted, as not many general public technical references can be found. It is the opinion of the authors that this circumstance is the main reason of the slow and unequal adoption rate of PLC technologies in the different utilities. The causes for these non-existing standard deployment guidelines include reasons such as application of the technology on real grids being far from academics, electricity grid being a transmission media that needs skilled technicians to be handled and that is not accessible to the general public (with the exception of the in-home segment), and PLC technology not being a conventional transmission media for telecommunication specialists. This paper will contribute to solve these aspects, providing guidelines for the deployment of Smart Metering systems.

This paper is organized as follows: Section 2 includes a review of the Smart Metering systems; Section 3 is focused on PLC systems and their evolution; Section 4 describes the status of the PLC systems used to support Smart Metering systems; Section 5 focuses on the key decisions to develop PLC systems for Smart Metering and Smart Grid applications; Section 6 provides specific guidelines for PLC-based Smart Metering deployments; Section 7 includes the challenges that will make PLC systems better serve the evolution of Smart Metering networks into Smart Grid networks; and Section 8 highlights the main conclusions of the paper.

2. Review of Smart Metering Systems

Smart Grid is a wide scope concept that in most energy distribution utilities starts with the so-called Smart Metering [12–15]. Smart Metering systems are also referred to as Automatic Meter Reading (AMR) in literature [16–21], and the infrastructure they rely on is referred to as Automatic Meter Infrastructure (AMI). However, Smart Metering is more than the basic remote meter reading capability and the ability to operate over smart meters (e.g., connect/disconnect), and may become the door to new services for energy efficiency [20–22]. These new services for energy efficiency are a subgroup of all the functional elements included in the wider Smart Grid for electricity distribution utilities, inside the advanced grid control systems that a Smart Grid requires. These new services are [23]:

- *Distribution Automation Systems* to control remotely the substations;
- *Energy Management Systems* to gather information from remote sensors, meters and other devices so as to analyze, control and plan the entire electricity grid;
- *Intelligent Network Agents*, as intermediate points collecting data of the grid, interacting with control centers and taking non-centralized decisions on local switching and control functions;
- *Demand Side Management Systems* to reduce consumption in the grid and optimize the global performance;
- *Asset Management Systems*, as complete and updated inventory systems of the facilities and equipment of the grid;
- *Geographic Information Systems* to add geographic data to the electricity grid operations for the optimization of the planning activities, and the detection and recovery of faults;
- *Grid Modeling, Simulation, and Design Systems* to obtain the best results minimizing operational risks.

Smart Metering systems need to provide both the basic functions needed for the remote meter reading, while at the same time they provide the real-time capabilities to access the smart meters in real time for the purposes of connection and disconnection. Smart Metering systems should be based on technologies that will make them come closer to the Smart Grid desired extended functionally, making the infrastructure they rely on, capable of offering increasing throughput to the communications network, and developing that infrastructure with the support of the electricity grid in such a way that the communications network itself, through the usage of the proper communications technology, offers information on the grid status and geographical connectivity.

3. Review of PLC Systems

PLC systems have been used in electricity grids for over a century. PLC technology offers the inherent relationship with the underlying grid in such a way that circumstances related to performance and availability can be associated to grid events. PLC, as explained in the next sections, refers to different variations of the same communications concept. Making a good combination of the different PLC technologies in the various segments of the grid, a PLC-based Smart Metering deployment may be arranged, so as to easily evolve towards a Smart Grid infrastructure.

3.1. Evolution of PLC Technology and Systems

The origins of PLC technology date at least back to 1918 in Japan, as [24] states in relation with the first test and commercial operation of PLC for voice telephony over power lines. PLC ideas were even generated earlier at the end of the 19th century, with certain patents claiming voice and data transport over any type of wired media including power lines. Few years later, the first experiments were carried out with this flourishing technology in the USA, Europe and Asia [24], in such a way that by 1927 PLC had been widely adopted [25]. The first implementations of PLC were intended for long distance applications in HV power lines (high power transmissions around 50 W and tens of kilometers covered using frequencies from 50 kHz to 300 kHz [25]), where regular telephone lines were performing worse than PLC due to the weakness of the poles used, and the interferences among power and telephony lines that often occurred (economic aspects may also be mentioned). These initial voice communications evolved to include low-speed data transmission, including the evolution to highly efficient digital communications for operational services [26] and the recent knowledge transfer from the BB PLC for access and in-home progresses [27,28].

However, PLC applications for meter reading (1897 as per [29], and 1903 as per [30]) were even earlier than voice applications. After the massive adoption by electricity utilities of long distance PLC transmission over HV lines, it was in 1930 [31], and more consistently in the 1950s when a group of companies [32] developed a PLC system for central load management, with the objective to control load peaks in the grid. These systems are the PLC systems known as "ripple control", and apart from the fact that some of them still survive in our days, they have the privilege to have continued the non-voice application uses of PLC technology, thus being the predecessors of Smart Metering and Smart Grid solutions.

Reference [9] offers a sound and complete classification of PLC systems, from the technology point of view. It focuses on the most evident aspects of the technology, such as the frequency band, the bandwidth, the data rate and the communications range achieved. Thus PLC systems can be classified as follows:

- Ultra-Narrowband (UNB) PLC. These systems work in either Ultra Low Frequency (0.3–3 kHz) or in the Super Low Frequency (30–300 Hz). "Ripple control" systems can be considered a historical example of this group of PLC technologies, even if these ripple control systems were one-way communications. These UNB systems convey very low data rates (roughly 100 bps) at tens or even one hundred kilometers.
- Narrowband (NB) PLC. These systems use the frequency band from 3 kHz to 500 kHz that include the European Committee for Electrotechnical Standardization (CENELEC) A band (Europe, 3–148.5 kHz), the Federal Communications Commission (FCC) band (USA, 10–490 kHz), ARIB band (Japan, 10–450 kHz) and Chinese band (3–500 kHz). These technologies have a range that depending on the power lines can reach from hundreds of meters to some kilometers. NB PLC technologies can be further classified as:
    - Low Data Rate (LDR) NB PLC. Single carrier technologies capable transmitting a few kbps;
    - High Data Rate (HDR) NB PLC. Multicarrier technologies capable transmitting hundreds of kbps.
- BB PLC. These systems operate in bands from 1.8 MHz to 250 MHz, covering distances from hundreds of meters to kilometers, and providing data rates from several Mbps to hundreds of Mbps.

Different applications have been associated to different types of systems through history. Two sections of the evolution can be distinguished, focusing on the NB or BB nature of the system:

- Narrowband PLC systems evolution (UNB and NB):
    - Ripple control systems were the first example of 'demand side management' in the middle of the 20th century. It used unidirectional UNB PLC, managing to couple the PLC signal from the MV to the LV, and reaching certain loads that could be disconnected from the grid, managing to reduce the consumption, and thus the peak load curve. These systems were enhanced to include some basic tariff-based meter adjustment, as a very basic seed of Smart Metering systems.
    - First Smart Metering systems were initially implemented also with UNB PLC. They are still used in some cases where meters are dispersed over broad geographical areas, and very limited non-PLC technological alternatives exist. In the last 20 years, two-way automatic communications system (TWACS) [33,34] and Turtle Systems [35] have spread their deployments, and have faced the criticism of the very limited scope of the functionalities that can be implemented in the Smart Metering domain with such low data rates.
    - The settlement of the Smart Metering concepts came in the 1990s with the advent of the EN50065 regulation (specifically in Europe). The upper part of the CENELEC A band is the common factor that has de-facto been reserved worldwide for PLC applications. Many proprietary systems were developed in the early part of this period using NB PLC. Some of them evolved to standard status, and some of them remained proprietary. And some others were standardized, but never produced any field-deployed system with a sufficient scale. Among these systems we can mention American National Standards Institute (ANSI)/Electronic Industries Alliance (EIA) 709.1 (LonWorks, becoming ISO/International Electrotechnical Commission (IEC) 14908-1 in 2008), IEC 613334-5 parts, and specific vendor solutions

(ON Semiconductor, STMicroelectronics, Yitran and Adaptive Networks among others, offering LDR NB PLC solutions, with data rates ranging from 1200 bps to 4800 bps). One of the "concepts" developed in this period was the application layer that these systems used, and the object model it managed (Device Language Message Specification (DLMS) and COmpanion Specification for Energy Metering (COSEM), respectively [36]).

  - Smart Metering systems, projecting themselves into the Smart Grid domain have been a reality with the development and massive deployment start of HDR NB PLC systems. Since the early attempts of HDR NB PLC systems with orthogonal frequency division multiplexing (OFDM) [37], inheriting the concepts of the multi-carrier modulation (MCM) of IEC 61334-5-4, it was not until PoweRline Intelligent Metering Evolution (PRIME) and G3 system definition crystalized that Smart Metering PLC systems could find a route to orientate the industry efforts towards non-proprietary, feasible, interoperable and field-proven solutions that were prepared for the needs of a Smart Grid. These systems were deeply analyzed by Open Meter project [38] (as a consequence of mandates M/441 [39] and M/490 [1]) and projected into the Institute of Electrical and Electronics Engineers (IEEE) 1901.2 and International Telecommunication Union (ITU) standardization roadmaps. These HDR NB PLC systems are able to support demand management programs, distribution automation systems, outage management, reduction of energy usage, decrease of network losses and local balancing. These applications do need technologies that are prepared to support their requirements, but the basic communications technology alone does not provide such functionalities [6]).

- BB PLC systems evolution:
  - Early implementations of BB PLC systems came in 1997 with the first tests for residential Internet access in UK with Norweb Communications and Nortel [40]. The products used were prepared to transmit data rates around 1 Mbps, that for the time they were intended were close to alternative commercial offers (e.g., Asymmetric Digital Subscriber Line (ADSL)). Very short time later, companies like Ascom and Main.net actively convinced utilities all over the world to engage with trials of different scope and scale to provide Internet access to their customers, within the context of the "communications bubble" of the 2000s.
  - The non-stoppable evolution of DSL technologies, together with the consolidated HFC alternatives made Internet access interest vanish, even if projects like Open PLC European Research Alliance (OPERA) [41,42] led most of the research and development (R&D) initiatives around BB PLC for the access segment.
  - BB PLC interest was reoriented for a segment that could complement the BB Internet access penetration, and many initiatives (Homeplug [43], Universal Powerline Association (UPA) [44], HD-PLC Alliance [45] and HomeGrid Forum [46]) developed solutions to provide BB PLC connectivity. Standardization bodies consolidated these developments in the form of standards for in-home, both in IEEE 1901 [47] and ITU G.hn [48].
  - However, the interest of utilities on BB PLC did not vanish with the Internet access deception. OPERA 2 [49] managed to re-orient the know-how gathered in BB PLC in the access segments, to search for electricity operational applications of BB PLC. Thus the possibility to communicate Secondary Substations (SSs) among them through BB PLC,

leveraged existing knowledge, and BB PLC products that could serve in-home environments, were adapted to produce industrial solutions that together with coupling units for MV cable connectivity, managed to provide deployable solutions for MV SS connectivity [50].

As a consequence, a group of state-of-the-art PLC technologies and solutions exist today. They have been developed and applied in different segments of the grid and for different purposes. Some of them are even well standardized and have the needed industry support.

3.2. Evolution of PLC Standardization

3.2.1. UNB and NB PLC Standardization

Standardization has not always been a priority in PLC systems. PLC priority has been historically to create systems that managed to work on real field conditions. Eventually, some parts of the systems were somehow promoted to standards, due to the adoption or the influence of the technology promoters. A good example of this statement were ripple control systems, that having their origin in the 1950s [51], were only standardized through [52] for receiver type testing.

NB PLC systems have also been subject to standardization efforts. In 1991, CENELEC issued the European Norm EN 50065-1+A1:2010 [53] and although some of the existing PLC proprietary systems remained proprietary, some others followed different standardization paths.

LonWorks [54] (ANSI/EIA/Consumer Electronics Association (CEA) 709 and ISO/IEC 14908-1 [55]) is the result of the system created by Echelon [56] and supported by the EIA and the CEA, initially for industrial and building automation. The ANSI standard has four parts, one for network control protocol (EIA 709.1-B, 2002), and three more for different physical media (EIA 709.2 is the one for PLC).

Konnex (KNX, EN 50090), promoted by Konnex Association [57], was initially created for home and building automation, as an evolution to harmonize three other protocols (namely, BatiBUS Club International (BCI), European Installation Bus Association (EIBA), and European Home Systems Association (EHSA)). Konnex version in EN 50090 ([58]), includes several communications media options, PLC among them.

The relevant examples in the IEC 61334-5 domain [59] are the International Standard IEC 61334-5-1 with a Spread-Frequency Shift Keying (SFSK) NB PLC system. IEC 61334-5-2 to IEC 61334-5-5 as Technical Specifications: IEC 61334-5-2 a FSK NB PLC system; IEC 61334-5-3 with a Direct Sequence Spread Spectrum Adaptive Wideband (SS-AW) NB PLC; IEC 61334-5-4 with a MCM with differential PSK, mainly for MV PLC; and IEC 61334-5-5 with Spread Spectrum Fast Frequency Hopping (SS-FFH) NB PLC system.

A complementary standardization effort took place for NB PLC systems with the so-called (DLMS/COSEM) [36]. The DLMS/COSEM is the application level and objects language that many smart metering systems worldwide use. DLMS/COSEM has its origins in the car-manufacturing industry in the 1970s. In 1980 an initiative called Manufacturing Automation Protocol (MAP) started to design a network standard to interconnect different electronic devices and machines in manufacturing plants [60]. This effort produced a communications suite [61], that at the application layer defined a protocol known as Manufacturing Message Specification (MMS), standardized as [62,63]. MMS became a reference for utilities when the American Electric Power Research Institute (EPRI) focused its attention on it. In the first half of the nineties, some European utilities and manufacturers started working to adapt MMS to the electricity distribution grid [64], and this work resulted in a simplified version of the protocol, and then called Distribution Line Message Specification (DLMS). DLMS was standardized by IEC TC57 as [65,66]. In 1996, the DLMS User Association was created, and inside the smart metering context, a whole new "abstract object" model (COSEM) was created based on the German Energy Data Identification System (EDIS, [67]). DLMS took the definitive name of "Device Language Message Specification", and together with COSEM addressed the overall market of utilities (not only electricity utilities), supporting non-PLC communication means.

The evolution of this second generation [51] standard systems follows with the introduction of OFDM systems, being PRIME and G3 the first instances to appear [68]. As it was mentioned at the beginning of the chapter, and specifically true for PRIME, the efforts were initially focused on producing an industry supported systems, that should be demonstrated on the field, and that could eventually be standardized. ITU-T initiated in January 2010 the G.hnem working group (hnem stands for "home networking aspects of energy management") with the objective of defining a NB PLC standard for energy management applications. In March 2010, the P1901.2 working group in IEEE, began to work on a NB PLC standard for Smart Grid Applications (LV and MV). Both ITU and IEEE have completed their standards, according to references [69,70].

3.2.2. BB PLC Standardization

The different BB PLC systems were developed and improved from the last part of the decade in the 1990s and in the first part of the decade of the 2000s. However, it was not until 2008 that the first formal standard appeared (ANSI, TIA-1113 [71]). This standard is mainly based on the HomePlug 1.0 specifications [72], one of the very first industry standards for BB PLC, with a great impact in the worldwide adoption of PLC systems for in-home environments.

However, the wider impact standards for the evolution of BB PLC systems have been prepared in IEEE and ITU. These standardization bodies inherited much of the PLC R&D of the first decade of the 21st century. An outstanding sample of R&D was the collaborative OPERA project [41]. OPERA was a multi-year project (developed in two stages) funded by the European Community that engaged a large and relevant community of PLC stakeholders. OPERA focused both on BB PLC technology and its applications.

The IEEE 1901 Working Group was created in 2005 to develop a standard for high-speed communication (over 100 Mbps), in both in-home and access environments [73–76]. Its efforts were completed in September 2010 with the definition of two BB PLC technologies [47,77,78] (it was not possible to get to a consensus on one single implementation) together with a mandatory coexistence mechanism allowing IEEE 1901 devices to coexist among them and with other BB PLC standards (*i.e.*, ITU G.hn).

The ITU-T G.hn Home Networking framework was established in 2006 to develop a recommendation for an in-home transceiver capable of operating over different types of in-home physical media (<1 Gbps [73,76,79]). Recommendation G.9960 [80] (PHY (PHYsical) layer) was issued in October 2009 and Recommendation G.9961 [81] (Data Link Layer) in June 2010. These recommendations do not target access applications.

4. Status of PLC in Smart Metering Systems

PLC is mentioned at the natural media to connect meters in Smart Metering systems [22]. Many of the PLC technologies that have been developed through recent history are discussed in [51,82]. Reference [9] provides a consistent organization and classification of these systems, with an especial focus on their standardization status. However, most of the references on PLC for AMR just analyze the nature and structure of the systems [19–21], with no clear reference on implementation or specific communication performance results.

BB PLC has been extensively developed for in-home and Internet access, as the existing standards show [47,48]. There are references [83,84] to the use of BB PLC for Smart Grid applications, but not many go further that the technology assessment and adaptation proposals for specific Smart Grid services (OPERA 2—second phase of OPERA project- published a deliverable assessing the feasibility of a BB and NB combination for Smart Metering [85]). Reference [86] refers to the usage of BB PLC for Smart Grid backbone connectivity, and Reference [87] includes recent examples of such deployments among a group of many other PLC applications. In [88–90], the utilization of BB PLC systems for Smart Grid applications is explored, but no major deployment of BB PLC as far as the smart meter, exists (there are, however, references to small scale pilots, such as the one in [91]). Reference [92] gathers most of the relevant information to develop MAC layers for PLC systems, depending on the intended application. Reference [93] refers mainly to NB PLC systems when elaborating on the options for the MAC.

Smart Metering is the most recent Smart Grid application based on PLC that uses NB PLC systems especially in Europe. The PRIME system is one of the systems used [94]. G3 [95] is another system of a similar nature [96,97]. PRIME system is being deployed extensively by Iberdrola in Spain [98]. PRIME technology evolution, from inception to field performance tests, can be followed in [68] where initial ideas are presented, and [36,99,100] covering the evolution of PRIME technology, from the early dates of PRIME's first implementation with interoperability assurance, to the first demonstration deployments, and the full deployment (over 100,000 smart meters) of a complete Smart Metering solution. Regarding the G3 system, references to small-scale field tests can be found [101–104], but no massive deployment result is known to date. G3 and PRIME are the basis of the most recent standardization efforts in IEEE (1901.2 [105]) and ITU (ITU-T G.9903 [106] and 9904 [107], respectively). Many of the tests and experiments cited and used in this paper are PRIME PLC technology based, and are representative of the behavior of new state-of-the-art HDR NB PLC systems.

Regarding PLC devices, references [108–111] analyze modems and their coupling interfaces. There are also some references [112–114] focused in the injection of PLC signals (mainly in the MV grid, as LV grid is less difficult), in the primary winding of the distribution transformers. A small quantity of papers focus on the characteristics of the communications devices for PLC communications in SSs as a harsh environment [115], and some other references discuss three phase nature of LV in substations [116–118]. Some recent studies deal with single phase-single transformer PLC injection [119,120].

LV grids are the next step of the segments to be controlled in utilities' grids. This control cannot take place without real-time telecommunication systems to access the grid. If PLC systems are to be deployed over the LV grids for Smart Metering purposes, real-time PLC systems should be offering the telecommunications for control systems on LV. Real-time PLC systems are many times associated to BB PLC systems. One of the reasons for this is that most of the existing NB PLC systems [16] are LDR NB PLC systems, just capable of accessing meter readings once in several days and they cannot be considered as real-time systems. AMR systems with such LDR NB PLC technologies are not able to offer real-time capabilities [121]. New generation NB PLC systems (*i.e.*, HDR) combine the real-time characteristics needed, with the low cost of the PLC platforms and deployments. This real-time data transfer enables optimized grid operation [122] and provides instantaneous information of the Points of Supply (PoS) in the LV grid [123]. This information may be used for the fast detection of faults in cables, voltage control, meter tampering detection, and LV monitoring capabilities, as those existing in MV and HV segments [124].

5. Deployment of PLC for Smart Metering and Smart Grid Systems

As it has already been stated, the electricity grid is a convenient resource for the transport of communication signals especially if they are applied for electricity grid related services. The integration of the telecommunications transport media in the core of the electricity assets, makes PLC a very attractive option, both in terms of availability and cost.

This section contains three subsections: the first subsection includes the electricity grid description, together with key elements of this grid in its relation with the PLC systems; the second subsection introduces the concepts that will influence the choice and architecture of PLC deployments; and the third subsection focuses specifically on NB PLC system deployments.

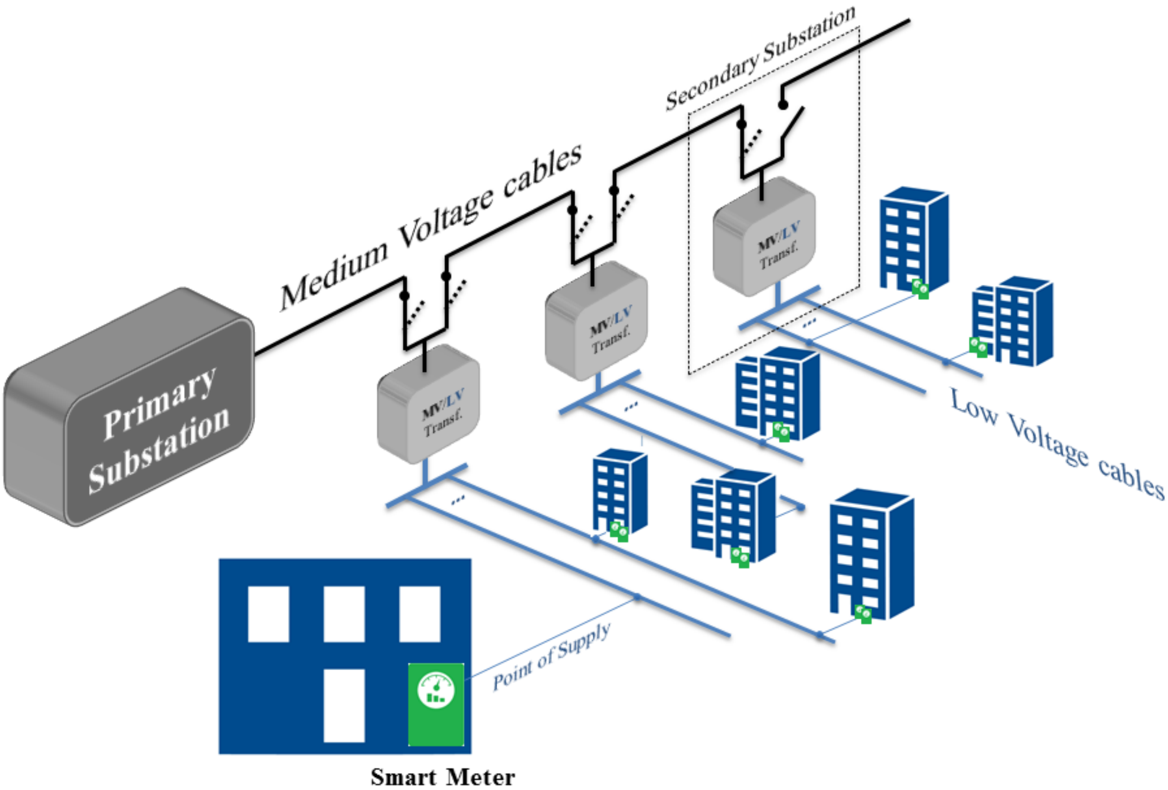
5.1. Grid Description

The electricity system is composed of four main elements: generation plants, transmission lines, substations and the distribution system. Electricity grids are different in the different regions of the world [125]. Grids are also different depending on the specific country we consider, and even its components are different depending on the age of the infrastructure.

The Smart Grid finds different instantiations depending on the specific need and segment of the network it is referred to. PLC, for the purposes of Smart Grid in distributed grids, is a telecommunications access technology and consequently it is used in the access segment of the electricity grid. This refers to the so-called MV and LV segments of the grid. MV and LV segments of the grid are the ones closer to the PoS (see Figure 1).

The MV segment [87] is the part of the grid that transitions from the HV grid to the so-called SSs (sometimes called transformer centers, as transformers from MV to LV are found in these premises). MV, depending on the cable configuration, may be classified as overhead or underground; this classification is not only important in terms of the cost and difficulty when building the grid, but it is relevant for the applicability and performance of PLC communications. Impedance of the power lines [126] is different in both types of networks, propagation is usually favored in overhead scenarios, access to the cables is of a different nature (signal couplers need to be installed differently), and more important, architecture is different as overhead power lines present a bus topology with mechanical switches in parts of the grid, whereas underground power lines configure a point to point network (where the "points" are the SSs) which is very attractive for the control of the telecommunications network built on top.

Figure 1. Electricity distribution grid.



LV segment [89] is the part of the grid in direct contact with the PoS. The LV segment presents two main characteristic: the first one is its capillarity and heterogeneity, as it needs to reach everywhere with the minimum investment; the diversity of configurations and the number of different components installed over the years, are some of the factors to be considered to understand the diversity of this scenario; and the second one is the susceptibility to the customer premises, where loads (customers and their appliances) are connected and disconnected due to the need to provide the universal electricity access, and that have different electricity consumption patterns, and connect and disconnect a variety of different devices at different moments. This circumstance implies that impedances change in different parts of the grid, and that noises appear and disappear during the day and the season without any clear and traceable origin. As a consequence this variability of the physical transmission media leads to different telecommunication subnetworks ("subnetworks" are each one of the PLC networks associated to each specific SS) which may be considered unique in their characteristics and performance.

Notwithstanding the description above, it is often hard to generalize on the nature and structure of electricity grid, as these aspects are usually a consequence of the historical evolution of socio-economic conditions in the different regions. However, there are some factors that need to be addressed as they are important to understand how and if PLC is to be used for communications:

- MV segment. Voltage levels need to be considered in the design of MV PLC solutions. The absolute value of the voltage level is a critical factor to design the couplers that need to transition the telecommunication signals from the transmitters to the receivers through the MV grid.

- LV segment. Distances, amount of PoS, and its density in LV grid. These three parameters are presented together, as they are not independent variables (see [100]). If the distance between transmitters and receivers is too large (in terms of attenuation) for a specific implementation of a technology, or if the density of the PoS is low enough to favor repetition of the PLC signals (according to the switching concept in [119]), or if the number of PoS per subnetwork is not high enough to allow for a high enough economic return on investment, PLC might not be an attractive technology.

In a scenario where PLC turns outs to be a viable and adequate technology for any of the MV and/or LV segments (this is the case according to the deployment status of PLC systems for Smart Metering networks, due to economic reasons, e.g., [127], once PLC systems have been technically proven on field at a massive scale [128,129]), these aspects mentioned are the ones that need to be solved by the technology and the implementation of the PLC devices. However, there are a number of other aspects that need to be solved regarding the architecture of the system, and at operational system level. These other aspects are oriented to bridge the gap among the technology and the devices themselves, and the deployment on the grid to guaranty that the PLC network performs in such a way that it is capable of supporting the requirements of Smart Metering and Smart Grid.

5.1.1. MV and LV PLC Architecture

Electricity grids in the different areas of the world are fundamentally different [125], but not in their functional principles. Grids are different in aspects related to voltage levels, extension and reach of the MV grid, and consequently, the nature of the LV grid. A good example of this is the difference between the European and North-American model. The European model presents MV grid voltage levels typically ranging from 10 kV to 20 kV, both in overhead and underground distribution. LV grid on each SS covers typically 300 PoS, and distances reach as far as 200 m. MV to LV transformers are usually designed with a "star" configuration with 400 V between phases, and 230 V between phase and neutral. North-American model, as a contrast, is usually composed of voltages ranging from 4 kV to 34 kV in MV, and distances ranging from 15 km to 50 km. MV to LV transformers produce voltages of 120 V or 200 V depending on load types. Typical LV cable lengths are close to 300 m, with an average of 10 PoS per transformer. PLC signals may be injected between phase and neutral to 120 V.

This paper is focused on Smart Metering systems, which are being developed through Europe. It is consequently focused on the European topology. The next sections highlight the most important aspects of the model, under the light of the decisions to be taken for Smart Metering systems with PLC technology [87].

5.1.1.1. MV

MV topologies can be classified in three groups:

- Radial topology. Radial lines are used to connect the primary substations with the SSs, and the SSs among them by means of radial lines. These MV lines or "feeders" can be used exclusively for one SS, or can be used to reach several of them. Radial systems keep central control of all the SSs. These radial topologies show a tree-shaped configuration when they grow in complexity. Radial topologies are easier and cheaper to develop, operate and maintain, than other structures.

- Ring topology. Ring topology is a fault tolerant topology to overcome the weakness of radial topology when there is a disconnection of one element of the MV line that interrupts electricity service (outage) in the rest of the connected substations. A ring topology is an improved evolution of the radial topology connecting to other MV lines to create of redundancy. Independently of the physical configuration, the grid is always operated radially, but on the event of a failure in a feeder, other elements are maneuvered to reconfigure the grid in such a way that out-of-order lines are restored most of the times.
- Networked topology. Networked topology consists of primary and secondary substations connected through multiple MV lines. Thus, the reconfiguration options to overcome faults are multiple, and in the event of failure, alternative solutions may be found to reroute electricity.

5.1.1.2. LV

LV grids present more complex and heterogeneous topologies than MV grids. Among the causes for this, the following ones can be mentioned: extension and particularities of the geographical service area, the PoS (loads), country and utility specific operating procedures and standards, *etc*. A SS typically provides electricity service to several LV lines, with one or multiple MV to LV transformers in the same site. LV topology is typically radial, evolving to create branches connected to the prolonged feeders. There are also cases of networked grids, and even ring or dual fed configurations in LV networks. LV lines are typically shorter than MV lines, and their characteristics are different depending on the service area (see the case of Europe, as reflected in Table 1 [130]).

Table 1. Typical data for electricity grids in Europe. SS: Secondary Substation; and LV: Low Voltage.

Parameter	High density residential area	Low density residential area
Type of SS	Underground or on ground level inside a building	House-type or over a pole
Transformers per SS	2	1
Average number of customers per SS	250–320	100 (10–200)
LV feeders per transformer	6–8	6–8
Average length of the LV lines (m)	150	300 (100–800)
Type of LV line	Underground	Overhead
Customers per metering room	10–25	1–4

5.2. Grid Aspects with Influence in PLC Systems Design

The different aspects and characteristics of the grid impose constrains in the way PLC systems may be designed and implemented to the limit of their possibilities. The next sections cover the most important ones to be considered when one or more PLC technologies need to be chosen for a Smart Grid roll-out.

5.2.1. Communications Architecture: MV *versus* LV

The key point to develop the most appropriate architecture for the services to be delivered is to take a decision on which combination of PLC technologies are to be used in each segment of the grid, considering the constraints of the existing MV and LV grids topology. There is no single answer to this question, as the final configuration will be based on the bandwidth needed for the services to be provided, the existing electricity grid infrastructure, the existence of adequate technology and vendors, and the preferences of the utility.

If we consider just the high bandwidth requirement, a BB PLC (also referred to as Broadband Power Line (BPL)) solution could be deployed in both MV and LV segments; if, on the contrary, only metering constraints are considered, just a fully NB PLC solution may be deployed in both segments. Combinations of both approaches can also be found, with BB solutions in the MV segment together with NB solutions for LV segment [88]; this mixed approach can also be applied in areas of the utility in combination with the other two approaches in other parts. As an extreme solution for very specific and particular grids UNB PLC remains as an alternative [33–35].

5.2.2. Communication Characteristics of the Segments of the Grid

The selection of any architecture is always to be considered related to the physical aspects of the grid, which impose conditions and affect performance of the PLC technologies on top of them.

A first major effect to consider is the propagation characteristics of the power lines in each of the segments (MV and LV). Cable design and disposition (overhead lines favor propagation), and the isolation of the segment from the PoS (disturbing noisy loads are mostly connected to the LV, and do not affect the MV segment) need to be considered to see how to best favor PLC signal propagation (maximizing desired signal and minimizing existing noise).

A second major effect is related to the interfaces between MV and LV grid, *i.e.*, the transformers at the SSs. The effect of these transformers at the interfaces is to be considered if the PLC system is to be used in both the MV and LV segment. UNB PLC systems are known to be capable of traversing the MV to LV transformer at SSs. Thus, a simple PLC signal injection in the feeders at the primary substations can get this signal to appear at the PoS. This is simply not possible in BB PLC systems (typically in a frequency range from 2 MHz to 30 MHz [131]) and inconsistently in NB PLC systems [102]. The latter is a high-impact issue, as it is not possible to know in advance if the PLC signal is going to be coupled from the primary to the secondary winding of the transformers without any external coupler, and this can be a major deployment problem if no clear and general rule can be established. As a consequence, if we just make use of one technology without making use of the natural segmentation of the grid (MV and LV), the bandwidth will be shared in all the system (with the constraints and conditions of the MAC layer and the attenuation conditions of the different parts of the grid), reducing the available highest possible throughput.

5.2.3. Isolation of MV and LV Grid

The electricity grid is a fully connected network. This is strictly true if electricity signals (50 Hz or 60 Hz) are considered, as electricity can flow from the MV to the LV segment through the transformers in the substations. However, PLC systems make use of higher frequency signals, and depending on the range of the frequency to be considered and the physical characteristics of existing assets (mainly transformers), the connectivity of the systems presents itself in a different way, ranging from full isolation to complete communication transparency. This means that a PLC signal of some kHz could be partially transmitted from the MV segment to the LV segment, while a signal of some MHz would not be capable of going through the same transformer. The frequency threshold of this signal transfer from MV to LV depends on the transformers characteristics and other installation factors.

Thus the only way to ensure interference-free coexistence of PLC systems in the same grid is to fully separate frequency bands. If this separation cannot be achieved, the PLC system must offer a channelization of its resources (different possibilities; a coexistence mechanism is the preferred option), and in any case, this PLC system internal segmentation brings a reduction of the available throughput. However, and as it happens with any other communication system, self-interference of PLC systems is largely unavoidable due to the shared media characteristics of electricity grid, and the varying degrees of isolation of the different parts of the grid.

5.2.4. PLC Signal Injection at SSs

In those cases where the architecture is based on the injection of PLC signals at SSs, PLC signals are mostly concentrated in the segments where the injection takes place. A differentiation can be made between systems injecting PLC signals in MV and systems injecting signals in the LV grid.

If PLC signals are injected in MV, a further classification can be established concerning the configuration of the grid itself, as in overhead MV cables SSs are all of them connected in a bus, whilst in underground topologies, SSs are connected in a point to point topology. In bus topologies, PLC signals spread to different SSs and systems must be naturally prepared to capture the signals intended for them; in underground systems, undesired PLC signals (*i.e.*, signals reaching non-planned SSs) can be considered as plain interference.

If the injection is in LV grid, PLC signals are expected to propagate in the LV segment; typically, one substation feeds just one LV segment in a bus topology (there are exceptions in some networks, e.g., in UK, where a PoS may be simultaneously connected to several SSs). The difficulties regarding PLC signal injection are related to the reception of PLC signals coming from other SSs and LV segments, and the PLC signal connectivity of multi-transformers sitting in the same SS.

5.2.5. PLC Signal Repetition in the Grid

Whether in MV or in LV grid, signal to noise ratio in the different communication links determines the maximum distance that can be covered. If the distance is shorter than the reach needed by the adjacent communication points (either two SSs in MV, or the SS and a meter in the LV), the difficulty that this limitation may impose is the impossibility to communicate the two distant points, and this obstacle (if the chosen PLC system is fixed and the grid conditions—distance and/or noise—cannot be changed) can only be overcome if PLC signal repetition is possible. Depending on the type of grid (mainly overhead or underground), the possibilities to connect devices to the grid to perform this repetition are different. If the repetition is to happen on the overhead grid, cable access might be easy (Figures 2 and 3 for MV and LV, respectively); if the repetition is needed in an underground grid, the devices can only be placed in points where access to the grid exists (these places can be fuse boxes, street cabinets, meter concentrations, *etc*., Figure 4).

Figure 2. Medium voltage (MV) cables on poles.

Figure 3. LV cables on a street wall.

Figure 4. Fuse box location in a building.

5.2.6. PLC Performance Assessment

PLC communications networks are very special due to their constraints. The main constraint can be found in network configuration once the architecture has been chosen. In many telecommunication systems, network planning can be controlled deciding where network equipment is going to be placed (with limitations in each case: e.g., base stations cannot be placed in any location). In the case of the electricity grid, service points and the places where PLC signals must propagate are fixed, and more important, the characteristics of the grid itself (cable types, specificities, *etc*.) are generally not known, or known to an extent that does not allow predicting PLC behavior. Thus, if ex-ante planning is severely limited, ex-post performance assessment is needed to understand if the results obtained are in accordance with the needs, and to understand where any grid modification or network adjustment is needed. Performance assessment of point-to-point connectivity is easy to make and there are many procedures and best practices [132]. This is completely different for shared media technologies, and especially for those which are NB (control traffic consumes an important share of the useful bandwidth).

5.3. NB PLC Systems for LV Grid Communications

The most common use PLC technology for Smart Metering [16] is NB PLC. Although some tests and pilots have been performed using BB PLC technologies, and even real deployments with UNB PLC technologies exist, NB PLC is the prevalent choice for Smart Metering including both meter reading and real-time nature applications such as remote connection-disconnection of meters [133,134], and remote firmware upgrade capabilities to guaranty that new features can be taken to the field over the existing infrastructure. BB PLC systems have been deployed over electricity grids for commercial Internet access [135,136] and on the in-home segment for easy local area network (LAN) connectivity [74,79]. UNB PLC systems [33–35] have been used sometimes as a last resource option for really low-density and disperse areas, where no other technology options were viable from the economic standpoint.

The information available on the results of NB PLC big scale deployments in literature is limited, as can be checked in [10]. Widespread information on deployments is based on the technical aspects documented by manufacturers (both proprietary and non-proprietary systems), but unfortunately this information is often biased by marketing. Referring to information provided on the results of standard PLC systems, references [36,99,100] are the most explicit references found, and even if they just provide information of samples of the results, they are a valuable source of knowledge as Chapter 6 will show with references to related studies. On the academic side, research has traditionally been focused on the basic aspects of the underlying technology in the devices (modulation, coding) and systems (channel modeling, noise models, medium access control strategies).

The optimum deployment of PLC for Smart Metering requires previous knowledge of several specific features of the grid that will support this type of communications. These aspects will affect the PLC system behavior and, depending on their influence, different grid aspects and PLC parameters or functionalities should be adapted to improve the performance of the whole set. Details in this regard are given in next sections.

5.3.1. Low Level System Aspects

Low level system aspects are related to the basic physical layer of the PLC technology. Modulation is one of these important aspects, to be determined based on the existing physical conditions and limitations of the grid (mainly distance and noise).

Modern multicarrier modulation systems based on OFDM generally offer different modulation alternatives, trying to get the most of the state-of-the-art electronics, and at the same time offering maximum throughputs in benign communication channels. However, grid conditions do not always favor the usage of high throughput (and low noise immunity) modulations. Although PLC systems typically behave in an adaptive way to select the most convenient modulation for any given channel conditions, the feature does not come without the cost of burdening channels with control packet overhead to manage link conditions that might reduce the useful throughput. Smart Metering systems rarely tend to establish high duration communications with a meter, but rather tend to adhere to the polling procedure of getting meter reading one meter at a time. This fact, together with the circumstance that in open and interoperable systems, peers needing to adapt the modulation scheme might be taking non-optimal decisions based on the assumption that its peer has some sensitivity characteristics that are not real (e.g., PHY Robustness Management (PRM) is a feature that in PRIME systems allows to adjust modulation scheme—robustness and power—of the individual links in an end-to-end connectivity; this feature would need to precisely know the sensitivity of the peers to perform properly, as the assumptions and, subsequently, PRM messages may lead to build unstable subnetwork topologies), the possibility of establishing a fixed a modulation scheme is attractive to decrease system complexity.

As a complement to the above, the data provided in [36] is very useful to understand that the PLC communications layer is just one of the parts of the system. According to [36], Smart Metering systems make common use of DLMS/COSEM-like application layers [137], and work in such a way that a central element (the concentrator, placed usually at the SS) performs a polling procedure to get all the meter readings. The overhead described is such that the performance decrease produced from physical layer throughput to application layer meter readings can be calculated with a factor in excess of 200. Thus, and taking PRIME modulation maximum throughputs with different modulation schemes as a reference [138], a factor of 6 (the ratio between the maximum and the minimum throughput with PRIME) is not relevant in the overall throughput performance.

On the other side, PLC communication channels in LV electricity grid are harsh and exhibit an instantly changing nature (see summary of noise contributions in [139]) that may produce unavailability in channels working with Signal-to-Noise ratio (SNR) close to the limit of the electronics behind. The circumstance is exactly that of radiocommunications [140], where links are designed to allow for an instant fading of a certain quantity, as there is statistical evidence that such a circumstance will appear. There are studies on the nature of PLC channels modeled in terms of noise [141], but there is not a quantification of the fades or the statistics behind as probably the effort needs to study a representative amount of LV grid segments at the utility side of the grid, in different regions of the world. In the absence of such studies, a conservative choice of the lowest risk modulation is appropriate for a field deployment. This modulation scheme should be accompanied by an error correction scheme, e.g., in PRIME PLC systems this would be DBPSK with Forward Error Correction (FEC) that offers 20 kbps throughput at physical layer.

According to the PRIME cases studied in [100], the usage of DBPSK modulation with FEC produced application layer availability over 90%. There are other low level aspects that deserve attention. PRIME system needs to adjust these alternatives making selections among the different options. Other equivalent systems offer similar adjustable parameters. These parameters and aspects are:

- SAR parameter size. SAR is the acronym of Segmentation and Reassembly. PLC media are harsh, and the longer the packets sent are, the higher the collision and noise occurrence probability is. Reference [92] offers a way to obtain the Bit Error Rate (BER) and packet length correlation. PLC systems tend to reduce the packet size through segmentation to obtain better Frame Error Rate (FER) results, at the cost of increasing latency in the system.
- ARQ utilization. Reference [92] indicates that PLC systems should apply both FEC and Automatic Retransmission reQuests (ARQ) to improve packet reception success rates. ARQ comes also with a latency increase in the system.

5.3.2. High Level System Aspects

One fundamental characteristic of PLC systems in LV grid for Smart Metering purposes is that node locations are basically fixed. Typically, PLC signal injection takes place at SSs, in the secondary winding of MV to LV transformers. In Smart Metering systems, service must be delivered at the locations where smart meters are installed. There is no feasible way to modify the location of neither the SSs, nor the meters, as the latter are associated to the points were electricity service is delivered, and that location is the choice of the customer. This situation can be considered not too different from other technologies, where end service points are fixed. However, the main difference is based, first on the number of end-points, and second on the great difficulty to gain access to intermediate grid positions, where network nodes might be also installed to configure the desired network to fulfill given quality objectives. LV grids are indeed not an homogeneous set, but it is very common to find underground LV cables with low to inexistent access to them. Of course, there are also LV grids which make extensive use of both LV cables laid on walls or suspended on poles, where cable access could be easier. Both cable deployment structures can be found mixed in the different utility service areas, with a trend to find underground scenarios in urban areas, and overhead in suburban and rural areas. In any case, as this circumstance cannot be controlled by the electricity distribution company when facing a Smart Metering deployment, the situation implies that traditional telecommunications planning is virtually impossible, and system communications must rely on the existing nodes on the grid, that are in fact the service destination nodes.

The situation explained above has already been addressed from a network node functionality perspective in most modern NB PLC systems [94,95,142,143] with a variable degree of success. The way this issue has been addressed is through the definition of a “node repetition” functionality that utilizes the capillarity and big number of network nodes, to create a packet transport structure that allows any packet to reach any destination through the help of the nodes in the grid, e.g., PRIME system names this repetition functionality as “switching”, and bases this layer 2 capability in the ability of every node in the network to act as a “switch” to repeat (retransmit) any layer 2 packet which is intended for a node that hierarchically depends on it. The creation of "switches" is managed by the controller of the subnetwork, *i.e.*, the Base Node, that decides which service nodes are allowed to act as "switches" to help him cover the entire grid. The success of the layer 2 (e.g., PRIME) or layer 3 (e.g., G3, with 6LoWPAN [144]) protocols capable of defining the repetition solution is based in a combination of physical layer available throughput, together with the smart definition of the algorithms and packets structures to make repetition functionality subject to an agile implementation, capable of fulfilling close to the real-time objectives of technologies needed for Smart Metering systems as part of the bigger Smart Grid concept.

6. Deployment Guidelines for NB PLC System Deployment

There are several grid-related aspects that need to be addressed by electricity companies to define the best solution to be deployed in a PLC-based Smart Metering system.

PLC signals need to be injected at the SSs, and the way this is accomplished is fundamental for the system performance. Two aspects need to be considered in connection with the nature of both the SSs and the transformers. On one side, the scenarios with several transformers in the same premise (SS) must be addressed. On the other, single or three-phase injection must be considered in each one of the transformers.

SSs are not the only elements to be considered in PLC systems, as the rest of the LV grid influences system performance. To obtain the maximum performance, signal repetition is to be considered. This PLC signal repetition through network elements (different to the nodes which are the destination of the service), is a key enabler of the PLC coverage in areas of the grid especially difficult to reach.

The following sections will further elaborate the aspects summarized in previous paragraphs. Most of the concepts studied come from the analysis of PRIME PLC systems. On one side, PRIME is the most widely deployed new generation HDR NB PLC system; on the other, the conclusions can be considered general for other HDR NB PLC systems.

6.1. PLC Signal Injection in SSs

The electricity distribution system [145] is the part of the electricity grid closer to the PoS. At the core of distribution system are the SSs. The main components of the SSs are the distribution transformers that adapt voltage levels for customer electricity delivery. Customer distribution lines are connected to LV panels, which are then attached to the secondary windings of the distribution transformers. If a PLC system is to be connected to the LV distribution lines, these LV panels (bus-bars) will be the point of the LV grid to connect to.

6.1.1. Multi-Transformer Scenarios

In a typical SS there is usually more than one LV panel, associated either to one or several distribution MV to LV transformers. Multi-transformer environments are typical of dense urban areas, where the density of customers is very high, and the evolution of the area has made the LV infrastructure grow. The PLC connectivity of LV panels connected in multi-transformer environments is not generally known, and LV PLC connection among these elements is unclear.

LV panel injection in multi-transformer environments has been addressed in [145]. The lack of previous references dealing with LV signal injection may be attributed to the fact that traditional AMR systems have been proprietary solutions from specific system providers. The details of the solutions used for these multi-transformer situations probably remain the know-how of the parties involved in the deployments.

Reference [145] assumes that the connectivity among the various transformers in a SS cannot be determined from the existing electricity company database information, and it states that according to the tests performed in a group of representative substations a certain correlation exists between the connection of neutral wires of the transformers and the likelihood of having a variable quality PLC communications channel among the LV panels connected. However, as certain cases were found where the PLC communications channel established among the LV bus-bars, was not good enough for network performance, even if neutral connectivity among the transformers of the SS was modified to improve the PLC connectivity, and that only via an on-site test this physical connectivity at PLC frequencies could be checked, reference [145] proposed a PLC injection mechanism that has been proven optimal in such grids [100]. This mechanism is based in the connection of the so-called Auxiliary Nodes, which manage to extend Base Node (subnetwork controller) access to the different parts of the LV grid connected to other LV panels.

Reference [145] leaves several aspects open. One of these aspects is the connectivity of the Base Nodes. Ethernet and coaxial cables are presented as examples of this connectivity, but are not compared. Depending on the various implementation scenarios, Ethernet or coaxial cable connectivity offer different characteristics that need to be assessed based on specific equipment's possibilities to take the most convenient implementation decision. Some other connectivity options, such as wireless, could also be explored to obtain the expected results.

The second aspect that deserves attention is based on the figures of merit used to select Auxiliary Node against the multiple Base Nodes approach. Reference [145] selects the strategy based on the metric of the success rate, which is appropriate for conservative Smart Metering scenarios. However, reference [145] also states that latency results are slightly better in scenarios where the multi Base Node approach is used. This result needs to be combined with the time to retrieve all measurements, which is also reduced with the multi Base Node approach. Thus it may result that the multi Base Node approach could be suggested for Smart Metering deployments where the speed to perform tasks (e.g., meter readings collection) is the most important figure of merit. The only drawback of this strategy is that PRIME (the technology used in [145]) does not allow today the coordination of Base Nodes, so that overall PRIME collisions are minimized. However, these collisions could de-facto be small in multi-transformer environments where multiple LV panels do present a low PLC communications feasibility, as collisions are by default not present in isolated panels. As a consequence, it could be desirable to explore the possibility of developing intelligent devices able to dynamically select either Base Node or Switch Node capability that depending on the objective and the specificities of the scenario could apply the best resulting strategy.

6.1.2. Single *versus* Three-Phase Injection

Many electricity systems are three-phase systems. PLC LV signal injection at SSs takes place in a set of bus-bars in panels from where electricity cables flow towards the PoS. These panels are connected at the secondary winding of the MV to LV transformers. Inside the panel, three-phase and one neutral bars are found, mounted either on a metallic framework or inside a metallic enclosure.

The minimum requirement to inject a PLC signal is via two conductors (typically connected to one phase and one neutral cable, as most common LV connectivity from triangle—star MV to LV transformers configuration suggests. However, a three-phase system might offer the possibility of using all phases to inject PLC signal. PLC signal, when injected in phase and neutral, progresses through the conductors, and may be coupled to the rest of phases either capacitively or inductively (the explanation is to be found on the parasitic elements of the cabling or its layout, with cables running in parallel for long distances).

Reference [120] explores single *versus* three-phase injection in a NB PLC system [117,146,147]. The work mentions some early experiments using passive couplers to divide the signal coming from a two-conductor injection-prepared device to produce three-phase coupling. The conclusions of this simple configuration were discouraging, as transmit power within EN 50065-1 [53,148] regulations reduce transmitted voltage level by 6 dB, and even worst, at the reception path, being the coupling mechanism purely additive, the worst case phase noise is present. As a result, SNR shows a bigger degradation than with a single-phase injection, especially if the phase with the best noise situation can be used for the primary injection.

This same reference configured a second experiment to overcome the limitations of the former passive signal injection, together with EN 50065 regulation. A PRIME Base Node is used to configure a virtual three-phase active injection device, with the help of the so-called two Auxiliary Nodes. This “virtual device” shows certain limitations over a pure and intelligent three-phase injection system, as the results show. These limitations [99] are related to both the physical and the MAC layer. Physical layer is a limiting factor, as the injection at each phase tends to configure longer distance PLC links than those based on PLC signal repetition. Thus, typical signal fades, or more commonly high noise occurrences, in systems working near the SNR performance limit, get PLC hops compromised by these sudden noise burst, causing unavailability. From a MAC layer perspective, as three-phase transmissions are sharing the same PLC media, their transmissions must be coordinated, because without the coordination of the Base Node and the two Auxiliary Nodes, transmissions would not be optimized. Moreover, this coordination needs to take into account the rest of the network. Notwithstanding these considerations, the results obtained showed that the availability of the results obtained with the single-phase injection were slightly better than those of the virtual three-phase injection (99.5% to 99.1%, respectively). With such close results, it seems that there is room for the existence of a three-phase injection device, overcoming the limitations of the virtual device configured, that could be used in the context of more intelligent solutions to better control the behavior of its networks.

The implementation of these smarter three-phase solutions could possibly use some sort of MIMO techniques [149], and specifically should overcome the handicaps identified in this early experiment to bridge the gap of the performance seen, and to offer even greater availability in the context of more aggressive noise situations than the benign ones that can be presumed from the high figures of the availability results. The considerations that need to be evaluated in these designs are:

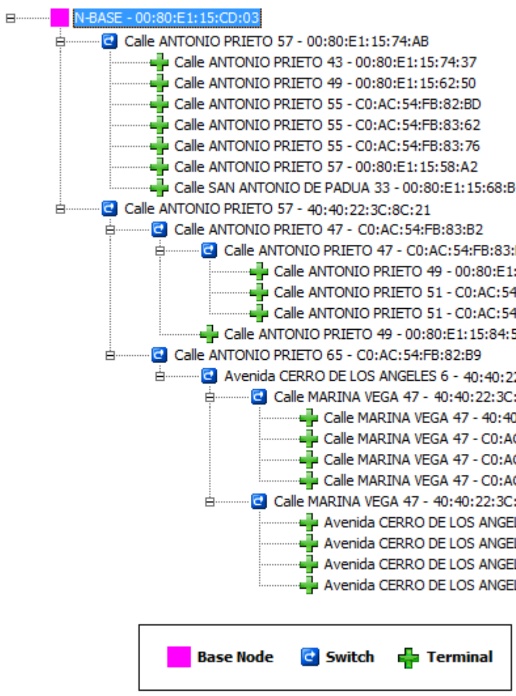
- Single or multiple transmission channels, and three reception channels, to avoid the noise additive situation seen in [120].
- Fix or rotating (among phases) transmission channel, to communicate with each PLC device in the most appropriate channel.
- Proper signal distribution algorithms from the three-phase injection device at the SS to the different PLC devices, to avoid links with SNR working close to the minimum thresholds.
- Adequate solutions for multi-transformer situations, where PLC signals leakage (interferences) could be affecting PLC transmission decisions.

As a general consideration, MAC layer decisions are the more important ones in these devices that should be capable of getting information from the network situation at its different levels, to optimize global performance by means of the limitation of the unavailability risks.

6.2. PLC Signal Repetition

The repetition of PLC signals has been proven at a massive scale in new generation HDR NB PLC systems, based on PRIME standard. As it has been mentioned before, the PRIME Base Node is the element injecting the PLC signal in the SS in a PRIME system. The Base Node is in charge of creating the PLC topology (Figure 5), which is composed of service nodes, some of them acting as terminals (*i.e.*, just connecting to the Base Node) and some others collaborating with the Base Node as switches (repetition elements) to gain access to places of the network (terminals) that are not able to receive or make their packets be heard by the Base Node. Thus, the switches are the elements appointed by the Base Node to make a layer 2 repetition of the signal.

Figure 5. Power Line Communications (PLC) topology in a SS.



In PRIME systems, the concept of repetition is just a specific state in the state machine of any network element. Generally, network elements are the service nodes inside electricity meters, but nothing prevents that some elements could exist, detached from the smart meters, and placed anywhere in the network (grid), whose basic function would just be to repeat (retransmit) PLC signal in difficult parts of the network. One clear example of such an element is the Auxiliary Node used in multi-transformer SSs. These Auxiliary Nodes are specifically configured to act as "switches" to repeat PLC signal in poorly or non-PLC connected transformers or bus-bars inside a SS.

The generalization of that sample device could lead to specialized devices placed in different parts of the grid to cover specific areas of it. These specific areas could be classified in two groups: the first one would be areas where SNR is low due to the presence of a high noise level; the second one would be areas where SNR is low due to the reduced level of the signal received from either the Base Node or any natural switch that could be created.

The value of the specialized repeater function is based on virtually "shortening" PLC links, placing an intermediate repetition point to help the PLC signal reach the desired end-point. Thus, SNR in both links (*i.e.*, the two segments configured with the repetition) would be improved by the increase of the signal level at the target end-point, and simultaneously increasing signal power and decreasing noise level at the link intermediate point.

Reference [119] offers the results of such an experience, focusing on the results of an experiment in a real LV grid, in a grid location showing an abnormal noisy condition. Two repeater configurations are tested, one with single-phase injection and another one with three-phase injection. In both cases, availability results are improved (from 16.2% to 37.8% with a single-phase repetition device, and to 47.9% with a three-phase device), demonstrating the feasibility of this procedure.

Apart from the pure functional feasibility, the more important aspect to consider in this strategy is the applicability of the concept on different real LV grids. The implementation of this strategy depends on their nature of the LV grid, as it needs grid accessible points that could be used if they present suitable characteristics to host this kind of repetition devices. In North-American style grids, LV is usually laid on poles, and the fitting of accessories for signal repetition would be straightforward, as the cables are easily accessible. However, in European style grids, with an extensive combination of overhead (on poles and on walls) and underground cables, the latter may pose a challenge due to the difficulty to access the cables needed to connect these devices. Fortunately, in Europe there are locations such as street cabinets and fuse boxes (e.g., Germany and UK for the former case, and Spain for the latter; all of them with suitable enclosures) where access to cables is granted, and that are located at a certain distance from noise sources (generally the customer premises) to produce the kind of configuration tested in [119].

There are specific circumstances where the configuration proposed, based on the high noise or big distances that could be present, may not produce the desired results (*i.e.*, SNR could not be improved to the needed extent). In these cases, the repetition concept can be applied if other non-PLC technologies are combined with PLC. Thus, extending the connectivity concept developed for multi-transformer SSs (*i.e.*, Ethernet connectivity), PLC repetition devices can connect via non-PLC technologies (radio technologies such as GPRS or 3G) to configure the link with the Base Node, and be placed as close to the noise sources as possible to maximize PLC signal level, and subsequently, the SNR.

The extension of this concept can be used to create technology combinations (PLC and other non-PLC options) that could improve overall system bandwidth and overcome noise problems.

6.3. PLC Performance Assessment

As it has already been discussed, PLC LV networks cannot be planned as some other telecommunications technologies, as the topology and electricity elements of the LV grid are not generally known, and their influence over PLC communication channels cannot be generally predicted. This situation, combined with the variability of the loads in the LV grid (heavily dependent on end-user consumption patterns, and always producing some kind of noise), make ex-ante planning efforts worthless for Smart Metering networks.

The alternative for network quality assurance in PLC based Smart Metering systems over LV grids is post-deployment performance monitoring and analysis. This monitoring should preferably be performed while Smart Metering networks are running in normal operation; however, the limited bandwidth characteristic of CENELEC A band LV Smart Metering PLC systems [53,148], even more constrained if low frequency band is avoided as it happens in modern systems such as G3 and PRIME, make it difficult to develop real time supervision systems in networks comprising thousands of end-points sharing bandwidths of tens of kbps. As a consequence, intensive performance monitoring of network behavior suggested in [100,150] appears to be the soundest alternative.

Performance monitoring is intended to characterize the performance of a NB PLC systems subnetworks in terms of availability and stability, the two main concepts that show how a Smart Metering network behaves. Availability is defined in [150] for devices as "*the accumulated time (relative to total time) when a device is accessible in the subnetwork*" and for complete subnetworks as "*related to the statistical values of the subnetwork elements as a group*". Stability is defined in [150] for devices as "*the capability of a subnetwork element to remain in a non-disconnected state*", and for complete subnetworks as "*related to the ability to maintain a stable number of registered elements*". These concepts are crystalized in different measurable parameters that are reproduced in Table 2, adapted from [150].

Once the stage for network monitoring process is over, and the data are elaborated with the existing grid information, both the SSs and the smart meters' behaviors can be studied. Grid data is fundamental to correlate communications network behavior with LV grid existing information, to serve the triple purpose of detecting the location of the problems, understanding the effect of grid configuration, and assisting grid operations.

The detection of the location of the problems is based on the identification of the elements (smart meters) in a LV grid that could be underperforming, through a correlation of the measured results and the grid location of these elements, and those that could subsequently communicate through them using PLC repetition capabilities.

Table 2. Detailed parameters proposed for PLC-based Smart Metering assessment.

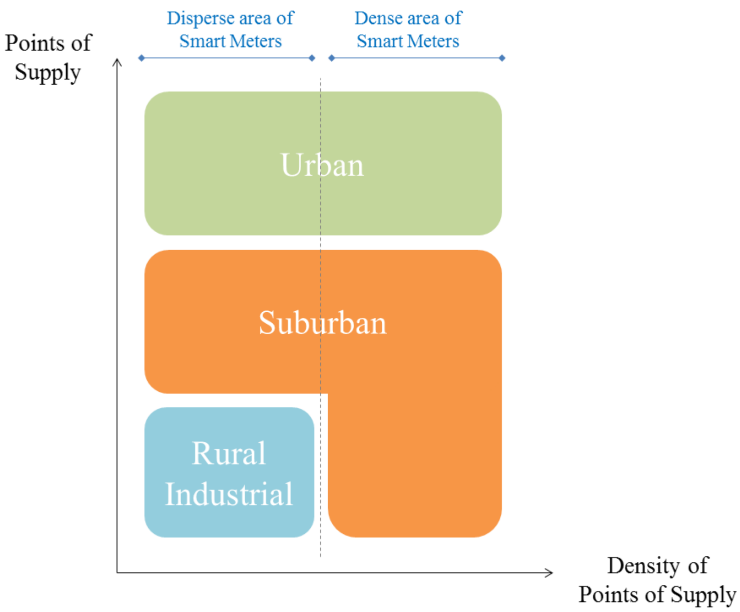
Group	Subgroup		Type	Parameter
A. Subnetwork evolution	A.1 Topology stability	A.1.1	Graph	Time evolution of registered nodes: number of nodes *vs.* time.
		A.1.2	Value	Number of changes in the network (increment or decrement in the number of registered nodes) per minute.
		A.1.3	Set of values	Statistical values (maximum, minimum, average and standard deviation) of the availability of communications nodes measured along time.
	A.2 Application data evolution	A.2.1	Graph	Number of correct reading attempts at each cycle.
		A.2.2	Set of values	Statistical values (maximum, minimum, average and standard deviation) of successful meter readings in each cycle.
		A.2.3	Set of values	Statistical values (maximum, minimum, average and standard deviation) of the duration of successful reading attempts in each cycle.
B. Individual communication nodes	B.1 Total accumulated duration of states	B.1.1	Set of values	Total time in each of the states.
		B.1.2	Set of values	Percentage of time in each state.
	B.2 Total number of disconnections at communications level		Value	Total number of times a communications node changes from registered to non-registered state.
C. Subnetwork availability	C.1 Communications availability	C.1.1	Set of values	Communications availability. Percentage of time (per element, such as subnetwork node, or groups such as meter concentration and the phase of the feeder in the concentration, line/feeder, transformer, *etc*.).
		C.1.2	Graph	Communications availability referred to the transformer, electricity line, distance to the SS (direct line or length of the line/feeder), nature of the line (overhead, underground, mixed), and meter concentration address.
	C.2 Meter availability	C.2.1	Set of values	Meter availability. Percentage of time (per element, such as subnetwork node, or groups as meter concentration and phase in the concentration, line/feeder, transformer).
		C.2.2	Graph	Meter availability referred to the transformer, electricity line, distance to the SS (direct line or length of the line/feeder), nature of the line (overhead, underground, mixed), and meter concentration address.
	C.3 Compared availability		Graph	Simultaneous representation of communication nodes and meters' availability.
	C.4 Subnetwork availability (communication node and meter level)	C.4.1	Value	Average availability of the communication nodes in the subnetwork.
		C.4.2	Value	Average availability of meters in the concentrators (subnetwork) influence area.

Table 2. *Cont.*

Group	Subgroup		Type	Parameter
D. Subnetwork topology	D.1 Most common stable states, with dependencies up to the Base Node	D.1.1	List	List of consecutive states, with start and end time for each node.
		D.1.2	Graph	Topology of the representations of the dependencies provided.
		D.1.3	Value	Accumulation of the number of Terminal and Switch nodes depending on a Switch.
		D.1.4	List	Inconsistent states (nodes with dependencies not represented in the tree).
	D.2 Instant topology of dependencies		Graph	Instantaneous topology graph, including the capability to represent evolving changes in dependencies.
E. Database information	E.1 Connectivity of the LV grid	E.1.1	List	SS, transformer, line/feeder, meter concentration and phase where meter is placed, together with geographical location (coordinates).
		E.1.2	List	SS, transformer, line/feeder, meter concentration, together with geographical location (coordinates).
	E.2 Meter characteristics		List	Meters characteristics, including the indications single- or three-phase.

The understanding of the grid configuration and its effects on network performance will be made based in the statistical correlation of common grid configurations with similar performance results. The model to be followed would be aligned with the scenario classification provided in [100] and represented in Figure 6.

Figure 6. Classification of PLC performance scenario.



The assistance in grid operation is a consequence of the close correlation of network behavior with the electricity grid configurations present in the network. Apart from the line and phase identification described in [100,151], which require a certain hardware deployment in the SSs, more simple approaches that immediately derive a correspondence of smart meters with associated transformers (based on the multi-transformer and Auxiliary Node configuration) explained in [145] can produce immediate improvements in grid operation.

Thus, individual device performance data are important to resolve evident problems in the network (*i.e.*, problems such as the failure of a smart metering device). However, more important than these individual results, is the aggrupation of the data of smart meters in the same location, to be compared with the same aggrupation in adjacent or related premises (through electricity infrastructure). The correlation of performance data must be grouped based on electricity infrastructure data. Reference [150] suggests to study monitored behavior considering the different parts of the SS subsystem, that can be further elaborated per each meter concentration (physical location where, in some countries, meters tend to be collocated), each phase in the meter concentration, each electricity line (feeder) in the SS, each LV panel in the SS, and each transformer at the SS. These set of grouped results may be used as the next sections highlight. These correlations need to consider the time dependence of the behavior, to enhance the perspective with the evolution of results over time, and to understand the influence of periodic underperformances in the network (mainly caused by noisy conditions associated to consumption patterns [152]).

The next sections provide the details of the application of the parameters shown in Table 2.

6.3.1. Subnetwork Evolution Parameters

This group of Smart Metering network data offers information on the time evolution of the total number of nodes connected to the Concentrator, with parameters that measure the fluctuation of this value over time (A.1.2 parameter in Table 2), the number of nodes accesses in each polling cycle, and the duration of each one of the read cycles.

The connected node graph (A.1.1) must be analyzed considering the trend of the curve to see if the subnetwork keeps an average of nodes regularly connected, to detect specific events that disturb the normal trend. If the appearance of these specific events is periodically distributed, these events need to be correlated against grid specific and regular circumstances that might create PLC disturbing noises in the system. This analysis must be completed with A.1.3 statistics to locate and mitigate the LV grid noise.

Any application level data progresses through the PLC communications technology. Thus, communications layer behavior will directly affect application level results. However, subnetwork communications behavior does not completely explain the application data curve evolution (A.2.1), and it must also be separately analyzed to observe the information transfer success, and the duration of each data read cycle (A.2.2 and A.2.3).

6.3.2. Individual Communication Nodes Parameters

Topology is the basic structure that defines communication paths among nodes in a hierarchical PLC subnetwork. The topology is related with the states and duration of these states (B.1.1 and B.1.2 parameters) in the different Service Nodes connected to the Base Node. The number of Service Nodes in a Topology in “switch” state, together with a measurement of their dependencies, explains many of the communication difficulties, and latency increments at application level data transactions.

Disconnection event (B.2, at communications level) is related with the PLC loss of communication with the Base Node (communication device located in the Concentrator). Subnetwork stability is higher when a small number of individual nodes disconnections exist; thus, the existence of a low number of disconnections is an indication of subnetwork stability. Subnetwork stability results affect application level data transfer, seriously handicapped in unstable subnetworks.

6.3.3. Subnetwork Availability Parameters

Any service node in a PLC subnetwork is "available" during a certain time of its life cycle, depending, first of the state in which it is from a communications level perspective (C.1.1 and C.1.2), and second, of its capability to "respond" when it receives an application data level "request" (C.2.1 and C.2.2 parameters; request and response cycles as defined in [36,100]).

Communications layer availability and data application layer must be compared at individual node level (C.3) to detect anomalous circumstances where the two parameters do not show a good correlation. If communication layer availability is high, and data application layer availability is not, this is a sign that demonstrates that the smart meter does not perform well at application level.

From a subnetwork perspective, the complete subnetwork behavior can also be assessed with statistical data (e.g., average performance); these results are of interest to compare subnetworks, and detect those which could be performing under the average values, and could be reflecting abnormal subnetwork or grid situations.

6.3.4. Subnetwork Topology Parameters

Each SS is made of a certain group of electricity assets (cable, loads, configurations, *etc*.; and specifically, a certain interconnection and disposition of the smart meters) that provide contour conditions to the way the PLC subnetwork behaves (see classification as per [100]), e.g., from a PLC communications perspective, these conditions configure the topology of "switches" and "terminals".

Thus if we are able to represent the different instantaneous topologies of the subnetwork (D.2), we could be studying the grid and load circumstances around the specific abnormal events, in an ex-post analysis.

Interestingly, topologies tend to be stable in PLC subnetworks. If we can represent the most common stable situations (D.1.1 to D.1.4), we will be able to analyze the subnetwork without the non-common states obscuring the general perspective of the stable PLC subnetwork states.

6.3.5. Database Information Parameters

Electricity utilities maintain databases that gather the most relevant aspects of the assets in the grids they manage. From a traditional perspective, the data information was consolidated in data models created for the purposes of traditional non-AMR purposes. This characterization of the assets is not necessarily the one needed for the design, operation and maintenance of PLC-based Smart Metering networks. Even more important, the quality of the data contained in these databases, as normal traditional operations were not affected, ranges from the total lack of data to a certain degree of adherence to the needs of Smart Grids, with a variable degree of accuracy.

If the results collected with PLC networks are correlated with the existing database information, we can, e.g., map the real topology of the electricity grid, getting to know which smart meter is connected to which SS and LV line in it (E.1.1 and E.1.2), improving database information quality. This application can be taken further as [151] demonstrates.

E.2 parameter is important, as it identifies the smart meters which are connected to one or the three phases. Three-phase connection may become important to develop PLC signal repetition intelligent strategies.

7. Challenges of NB PLC Systems for Smart Grids

The need of Smart Metering deployments and the conviction that this emerging application will be the origin of Smart Grids has given impulse to a significant development of both BB and NB PLC systems for utility operations. This necessity has been recognized by different national regulators (e.g., Spain [133,134], France [153], UK [154]), and according to the European Commission M/441 [39] and M/490 [1] mandates, should evolve to be consolidated in Smart Metering and Smart Grid standards, respectively.

7.1. NB PLC Systems Optimization

NB PLC systems deployed on field, have been usually deployed following rules deduced and dynamically adapted while the systems were being commissioned. These deployment decisions have helped to deploy the systems in a straightforward way, and probably could be optimized if new experiments are carried out, or specially tailored solutions are implemented in each one of the individual and different SSs.

The first new generation NB PLC systems have been born in an environment where it must have been the need to demonstrate functionality, with a focus on interoperability. The objective of improving the performance of the systems has been postponed. The fundamental target was to create an industry with a plethora of smart meter manufacturers providing cost-effective and interoperable smart meter platforms. Thus PHY layer performance objectives have been inexistent and grid noises that could be considered trivial for certain smart meter hardware platforms can be catastrophic for other smart meters, biasing the technology performance results. At MAC level, different implementations are prepared to offer stability, while others try to make topologies "converge" as soon as possible. The former systems take more time to evolve to a stable topology, while the latter ones usually converge in a quick way, but when traffic appears in the network, tend to show a lack of stability that does not consolidate in a stable network until the network understands which ones are the preferred "switches". It is clearly needed to define minimum performance objectives at PHY level, and different profiles of MAC figures of merit regarding the different applications (Smart Metering, in-home applications, *etc*.).

BB PLC systems for utility applications do also have an opportunity complementing NB PLC systems, or replacing NB PLC to some extent or in some parts of the grid, as will be covered in Section 7.3. These systems are either pre-standard systems, or evolutions from commercial in-home BB systems, adapted to perform generally in utility MV environment. The market for these systems still needs to be created. On one side, MV is not a straightforward environment, as couplers to MV power lines must be found and integrated in MV switchgears. Both the lack of low cost solutions and the diversity of switchgears and operational procedures, usually make utilities struggle to find adequate market solutions. Equally important, MV grid knowledge must be combined with BPL technology know-how, to produce planning rules which are easily translated into field-deployable solutions, with known performance parameters. If we need to use these systems in LV grids, the MAC layer solutions need to be developed in a similar way to the existing NB PLC systems, which have been able to overcome the existing deployment difficulties and performance limitations.

7.2. Electricity Grid and PLC Interaction Knowledge Development

The classification of the scenarios provided in [100] is a first derivate of the deeper classification that should be created to specially tailor smart metering deployment methods. Three-phase injection, and other important aspects might be used in each scenario if a further refinement of the results is provided based on a statistical analysis of the existing field data, when non representative results are excluded from it (noisy networks, bugs in the implementations, *etc*.) and comparable deployment solutions and metrics are used (e.g., systems such as PRIME offer different implementations of the PRIME specification, without comparable performances at PHY level, and different ways of implementing MAC policies together with the controllers of the subnetworks; these elements should be placed on equal terms and conditions to derive the appropriate comparisons).

Furthermore and fully aligned with the PLC deployment objectives, PLC provides an opportunity to develop the Smart Grid concepts. These concepts are both developed with the use of performance results to improve grid knowledge, but must exceed this limited scope by means of application of PLC to the knowledge of the grid, as covered in [151]. Connectivity identification (transformer, LV line identification and phase location of Smart Meters) is the top of the iceberg (customer asset management, technical losses reduction, fraud detection, transformer balancing, synchrophasors [155], *etc*.) of a group of applications that will open a new world of LV grid operations [156] (remote control of LV assets, with protection schemes similar of those in MV levels, *i.e.*, switches for line protection, operated over the PLC systems used for Smart Meter operation).

7.3. PLC and Other Telecommunications Technologies Combination

Smart Metering systems in CENELEC A band are certainly limited in bandwidth. As the CENELEC A band is not going to be easily expanded, other alternatives need to be identified and developed to increase the maximum bandwidth that could be used. This is probably a key consideration if PLC systems in Smart Metering systems need to be projected for Smart Grid applications in LV grids.

The combination of technologies (PLC and non-PLC) seems to be a clear alternative in this approach. Thus, a first improvement of this approach would be to combine NB PLC solutions from the SSs, with other non-PLC communications in the places where meter concentrations appear. Wireless (ZigBee, Wireless M-Bus, *etc*.) or wired technologies (RS-232, Ethernet, *etc*.) can be used from communications gateways in meter concentration rooms, in such a way that the communications among the meters do not interfere, affect or decrease the performance of the rest of the PLC network. The evolution from the existing systems would be immediate, as long as the smart meters are available, and would immediately increase the total bandwidth of the network. A side effect of this deployment configuration would be that each subnetwork could be deployed as if it were a pure communications network from the SSs as far as the concentrations of smart meters, controlling the performance of this network with a low quantity of devices in the PLC domain. As the controllability of the working network would be much higher, the deployment solutions could be fine-tuned for increased performance.

Another approach to expand the bandwidth available in this LV segment, would be to use BB PLC systems prepared to work in LV grid scenarios. This approach has several drawbacks. The first one is the lack of well-proven open technologies and available with general knowledge and low prices. The second is the allowable bandwidth (spectrum), because if BB PLC is to be used in LV segment, the use of PLC in MV segment would see its performance decreased due to the need to control the total bandwidth available. Alternatively, BB PLC could be removed from MV segment, although this might be a severe limitation in places where radio communications are physically limited to penetrate difficult environments (*i.e.*, underground SSs).

8. Conclusions

This paper has covered the strategic aspects of PLC systems applications over the electricity grid for the purpose of Smart Metering. The history, strong aspects and the constraints of PLC systems have been shown, in order to understand how PLC may fit in the Smart Metering networks. The paper rationale is the need to further evolve these PLC systems, their design and their architecture on field, to make them capable of offering the functionality and performance needed for the Smart Grid.

The system decisions to make PLC systems adapt to each Smart Metering scenario have been elaborated in Section 5. The first aspect that needs to be considered is the communications architecture to be developed in the MV and the LV grid segments, where the throughput requirements are an important factor to be taken into consideration, together with the isolation level of the PLC systems used in the connection points of MV and LV segments, *i.e.*, the SSs. Once the architecture has been decided, the PLC signal injection at the SSs, and the capabilities of the PLC system chosen will condition the performance results obtained. To conclude the chapter, and being the NB PLC systems the most prevalent ones for Smart Metering networks, specific low level aspects recommendations are provided on the MAC layer, being packet size, FEC strategies and automatic retransmission the most important ones.

Section 6 includes the deployment guidelines for NB PLC systems. These guidelines are to be applied in both the SSs (injection of PLC signal from the masters of the system) and at the different points of the LV grid if signal repetition due to low SNR is needed. Signal injection strategy is heavily affected by the multi-transformer scenario described in the chapter, and by the nature of the signal injection (single- or three-phase). These guidelines will manage to obtain the performance results needed. In order to check the real performance obtained on field, a PLC network assessment procedure is described, together with the interpretation of the results.

The paper ends with the challenges that PLC systems face in their evolution to fit the needs of Smart Grid networks. On one side, the need to further optimize existing PLC system is highlighted. On the other, the interaction between PLC systems and the grid is shown as a factor that needs to be used both to improve PLC systems performance, and to obtain a better knowledge of the grid itself. As a final idea, the combination of PLC and non-PLC technologies is suggested as a possibility to pave the way towards Smart Grids.

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Author Contributions

Alberto Sendin is the main author of this work. This paper provides a further elaboration of some of the results associated to his Ph.D. dissertation. Pablo Angueira has supervised the Ph.D. work and thus has contributed to the design and discussion of the results. Ivan Peña has designed the structure of the contributions to fit them into a review of PLC based smart metering methods and systems. All authors have been involved in the manuscript preparation.

Conflicts of Interest

The authors declare no conflict of interest.

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