For the Grid and Through the Grid: The Role of Power Line Communications in the Smart Grid

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***Abstract*—Is Power Line Communication (PLC) a good candidate for Smart Grid applications? The objective of this paper is to address this important question. To do so we provide an overview of what PLC can deliver today by surveying its history and describing the most recent technological advances in the area. We then address Smart Grid applications as instances of sensor networking and network control problems and discuss the main conclusion one can draw from the literature on these subjects. The application scenario of PLC within the Smart Grid is then analyzed in detail. Since a necessary ingredient of network planning is modeling, we also discuss two aspects of engineering modeling that relate to our question. The first aspect is modeling the PLC channel through fading models. The second aspect we review is the Smart Grid control and traffic modeling problem which allows us to achieve a better understanding of the communications requirements. Finally, this paper reports recent studies on the electrical and topological properties of a sample power distribution network. Power grid topological studies are very important for PLC networking as the power grid is not only the information source *but also* the information delivery system - a unique feature when PLCs are used for the Smart Grid.**

***Index Terms*—Smart grid, power grid, distribution network, power line communication, power line channel, distributed control, cyber-physical systems.**

I. Introduction

Digital communication over power lines (PLs) is an old idea that dates back to the early 1920s, when the first patents were filed in this area [1]. Since then, utility companies around the world have been using this technology for remote metering and load control [2], [3], using at first single carrier narrowband (NB) solutions operating in the Audio/Low Frequency (LF) bands that achieved data rates ranging from few hundred bps to a few kbps. As technology matured and the application space widened, broadband (BB) PLC systems operating in the High Frequency (HF) band (2-30 MHz) and achieving data rates up to a few hundred Mbps started to appear in the market. In the last few years, industry interest has grown around the so-called "high data rate" NB-PLC based on multicarrier schemes and operating either in the CENELEC bands (3-148.5 kHz) or in the FCC/ARIB bands which extend up to ~500 kHz.

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PLCs are also used around the world to provide BB Internet access to residential customers, BB LAN connectivity within home/office/vehicles, command and control capabilities for automation and remote metering [4], [5], [6], [7]. The basic incentive for using PLCs is that the power grid provides an infrastructure that is much more extensive and pervasive than any other wired or wireless alternative, so that virtually every line-powered device can become the target of value-added services. In spite of the PLC promise as an enabler of a multitude of present and future applications, PLCs have not yet reached the mass market penetration that is within their potential.

Today, a new compelling reason to use PLCs is today emerging: the recent impetus in modernizing the aging power grid through an information highway dedicated to the capillary management of the energy distribution, the so called *Smart Grid*. It is commonly recognized that the Smart Grid will be supported by an heterogeneous set of networking technologies, as no single solution fits all scenarios; nevertheless, an interesting question is whether the Smart Grid will have a pivotal role in fostering the success of PLCs in the market. The objective of this paper is to analyze critically the role of sensing, communications, and control in the Smart Grid and, at the same time, clarify what PLCs can offer today and what is unique to PLCs for Smart Grid applications.

A. The Smart Grid Design Challenge

It is broadly believed that the growth of energy demand has outpaced the rate at which energy generation can grow by traditional means. Additionally, many governments agree that greenhouse gas emissions need to be contained to control or prevent climate change. The necessity of modernizing the electric grid infrastructure around the world is both the consequence of the limited investments made in it in the last decades, as well as of the result of new requirements that emerge in the safe integration of utility scale Renewable Energy Sources (RES) feeding into the transmission system, Distributed Energy Resources (DER) feeding into the distribution system or the home, decentralized storage to compensate for the time varying nature of wind and photovoltaic sources, Plug-in (Hybrid) Electric Vehicles (PHEV) that may cause large load increases on sections of the grid, microgrids, and in allowing active participation of consumers via Demand Side Management (DSM) and Demand Response (DR) programs - all of which are advocated as the sustainable solutions to our energy crisis.

Balancing generation and demand at a very granular scale requires the integration of additional protection and control technologies that ensure grid stability [8], [9] and that are not a trivial patch to the current distribution network. Power grids are designed to be managed through a rather old-fashioned centralized cyber-infrastructure model, referred to as Supervisory Control and Data Acquisition (SCADA). Hence, the concept of *Smart Grid* has emerged, encompassing the cyber-physical infrastructure including wide-area monitoring, two way communications and enhanced control functionalities that will bridge the present technological inadequacies of the SCADA system [10].

Since communications is such a fundamental element of the Smart Grid, the appropriate design for physical, data and network communications layers are today a topic of intense debate. Unfortunately, Smart Grid is today more a "vision" than an actual design. Quoting Tomsovic et al.: "*Although the available communication today is fast enough, the computation needed for such real-time control is still very complex and poorly understood*" [11]. For instance, DR and load shedding can potentially yield economic benefits and energy savings [12], [13], however the correct implementation of DR and, more in general, of DSM applications for maximizing system savings under stability constraints is still not known. For example, in [14] it is pointed out that: "*When demand peaks occur, reducing energy to a minimum seems like a valid solution, however this compromises system stability.*"

Simulations and small field trials - often conducted with cautious containment to prevent cascading failures - are insufficient to grasp fundamental threats to the global stability of the grid that can arise when dealing with a large scale system. In fact, still absent in most technical discussions are specific parameters of the monitoring and control functions that Smart Grid communications shall enable. Furthermore, the optimality at the level of sub-systems is no guarantee of an overall optimal design. As we discuss in more detail in Section IV-B, optimizing communications, control and sensing in a large decentralized cyber-physical system is a very complex and elusive problem. For instance, the results available on observability and stability of networked control systems are valid only under very restrictive assumptions (e.g. a single link with zero latency, a perfectly known system, etc.) [15], [16], [17], [18].

In order to design communication schemes and examine their efficiency from both a scalability and a distributed control point of view, it is of paramount importance to characterize statistically the Smart Grid information *source*, i.e. the power grid itself. As for any interconnected system, the dynamics sensed are highly coupled and dependent, an aspect that should not be ignored in managing, aggregating and prioritizing the network traffic. However, very little work has been done in this direction. Interestingly, in the case of PLCs, the characterization of the grid as an information source will also lead to a better understanding of the grid as an information delivery system, i.e. the grid *is also* the physical network medium.

B. PLCs and the Smart Grid

The debate on what is the actual role of PLCs in the Smart Grid is still open and while some advocate that PLCs are very good candidates for some applications, others express concerns and look at wireless as a more established alternative. There is no doubt that the Smart Grid will exploit multiple types of communications technologies, ranging from fiber optics to wireless and to wireline. Among the wireline alternatives, PLCs is the only technology that has deployment cost comparable to wireless, since the lines are already there. A promising sign, attesting the fact that PLCs have already exited the experimental phase and are a technology mature for deployment, is the central role that NB-PLCs have gained in Europe for supporting Automatic Meter Reading (AMR) and Advanced metering Infrastructure (AMI).

This said, there are two aspects that could hinder PLC market opportunities. One is the commercial pressure to jump on the bandwagon of Smart Grid applications with the wrong PLC technology. Especially in the US, PLC vendors are promoting the use of BB-PLC modems that were originally designed to support Home/Building Area Networks (HAN/BAN) or Internet access applications and not Smart Grid applications. These solutions have limited range and are likely to be over-designed for Smart Grid applications. A second impediment for the mass adoption of PLCs in the Smart Grid is the outcome of PLC standardization efforts. In the last couple of years, the PLC industry moved from a complete lack of standards to the opposite extreme of having four non-interoperable standardized technologies which have been either ratified (TIA-1113, ITU-T G.hn) or are close to final ratification (IEEE 1901 - which includes two PHY/MACs based on FFT-OFDM and Wavelet-OFDM) by three different Standards Developing Organization (SDOs). Interference between non-interoperable devices is the likely side effect of today's industry fragmentation. This problem has been somewhat overlooked in Smart Grid recommendations which *implicitly* assume that interference is manageable or absent. Fortunately, there are today standardized mechanisms that limit the harmful interference caused by neighboring devices. These mechanisms are commonly referred to as "coexistence mechanisms" - see Sect. III-E for more details.

In the following, we will mainly refer to three classes of PLC technologies[1]:

Ultra Narrow Band (UNB): Technologies operating at very low data rate (<100 bps) in the Ultra Low Frequency (ULF, 0.3-3 kHz) band or in the upper part of the Super Low Frequency (SLF, 30-300 Hz) band. An historical example of a one-way communication link supporting load control applications is Ripple Carrier Signaling (RCS) which operates in the 125 - 2,000 kHz and is able to convey several bps band using simple Amplitude Shift Keying (ASK) modulation. More recent examples are the AMR Turtle System which conveys data at extremely low speed (~0.001 bps) and the Two-Way Automatic Communications System (TWACS) that

[1] BB-PLC technologies devoted to Internet-access applications have also been referred to as Broadband over Power Lines or BPL, whereas LDR NB-PLC technologies have been referred to as Distribution Line Carrier or Power Line Carrier.

can carry data at ~60 bps. Despite the fact that these UNB solutions are proprietary, they are very mature technologies, they have been in the field for at least two decades, and have been deployed by hundreds of utilities.

Narrowband (NB): Technologies operating in the VLF/LF/MF bands (3 - 500 kHz), which include the CENELEC/FCC/ARIB bands. Specifically, we have:

- *Low Data Rate (LDR)*: Single carrier technologies capable of few kbps. Typical examples of LDR NB-PLC technologies are devices conforming to the following recommendations: ISO/IEC 14908-3 (LonWorks), ISO/IEC 14543-3-5 (KNX), CEA-600.31 (CEBus), IEC 61334-3-1, IEC 61334-5-1, etc. Additional non-SDO based examples are Insteon, X10, and HomePlug C&C, SITRED, Ariane Controls, BacNet etc.
- *High Data Rate (HDR)*: Multicarrier technologies capable of data rates ranging between tens of kbps and up to 500 kbps. Typical examples of HDR NB-PLC technologies are those devices within the scope of ongoing standards projects: ITU-T G.hnem, IEEE 1901.2. Additional non-SDO based examples are PRIME and G3-PLC.

Broadband (BB): Technologies operating in the HF/VHF bands (1.8-250 MHz) and having a PHY rate ranging from several Mbps to several hundred Mbps. Typical examples of BB-PLC technologies are devices conforming to the TIA-1113, IEEE 1901, ITU-T G.hn (G.9960/G.9961) recommendations. Additional non-SDO based examples are HomePlug 1.0, HomePlug AV (Extended), HD-PLC, UPA Powermax, and Gigle MediaXtreme.

C. Organization of Work

This paper starts with a brief historical overview of PLCs in Sect. II, and then reports on the status of the most recent PLC standards in Sect. III. The role of communication, sensing, and control in the Smart Grid is addressed in Sect. IV by looking at the required evolution path of today's SCADA systems and highlighting the most salient issues related to control and sensor networking, as well as tackling the problem of characterizing the traffic that needs to be supported. The specific role that PLCs can have in the Smart Grid is then addressed in Sect. V, where applications to the transmission and distribution parts of the grid are analyzed. We will then dedicate Sect. VI to discuss fundamental design issues. Recognizing that an important element of network design is the availability of planning tools for its deployment, we will review the state of the art in PL channel modeling in Sect. VI-A; furthermore, in Sects. VI-B and VI-C we will make the first step at analyzing the grid as both a data source and as an information delivery system - as PLCs naturally entail. Recommendations and final considerations are then made in Sect. VII[2].

[2] Initial results will be presented at the 2010 IEEE SmartGridComm Conference [19].

II. Historical Overview of PLCs

A. The Early Years

The first PLC applications put in place by power utilities involved voice and data communications over High Voltage (HV) lines which typically bear voltages above 100 kV and span very large geographical distances. HV lines have been used as a communications medium for voice since the 1920s (power carrier systems) [1]. In those years telephone coverage was very poor and engineers operating power plants and transformer stations used PLCs as an alternative way to communicate for operations management with colleagues stationed tens or hundreds of km away. When digital communications techniques were later introduced, only very low data rates (few hundred bps) were achievable for supporting telemetering and telecontrol applications [2], [3].

Another important driver for the original interest of utilities in PLCs was load control, i.e. the capability of switching on/off appliances responsible for high energy consumption such as air conditioners, water heaters, etc. Utilities have been using RCS since the 1930s to control peak events at demand side by issuing control signals to switch off heavy duty appliances [2]. RCS has been quite successful, especially in Europe, and its use has been extended to include other applications such as day/night tariff switching, street light control, and control of the equipment on the power grid. Interestingly, load control is attracting renewed interest as a means to balance generation and demand - see [12], [13] for an analysis of savings and benefits of DSM.

B. Ultra Narrowband and Narrowband PLCs

In the last couple of decades, several AMR/AMI solutions using PLCs, wireless, and phone lines have been deployed by utilities. As far as PLCs, first deployments involved UNB-PLC technologies like the Turtle System [20] and TWACS [21], [22]. Both systems use disturbances of the voltage waveform for outbound (substation to meter) communication and of the current waveform for inbound (meter to substation) communication [20]. TWACS is used for both AMR and distribution automation, while the Turtle System has been mostly used for AMR since the first available products (TS1) allowed only one-way inbound connectivity; a two-way version (TS2) of the Turtle System became available after 2002. A method that could increase the data rate of the TWACS inbound signal has been recently proposed in [23].

Recognizing the increasing desire for higher data rate, CENELEC issued in 1992 standard EN 50065 [24]. The CENELEC EN 50065 standard allows communication over Low Voltage (LV) distribution PL in the frequency range from 3 kHz up to 148.5 kHz. Four frequency bands are defined:

- A (3-95 kHz): reserved exclusively to power utilities.
- B (95-125 kHz): any application.
- C (125-140 kHz): in-home networking systems with a *mandated* CSMA/CA protocol.
- D (140-148.5 kHz): alarm and security systems.

CENELEC mandates a CSMA/CA mechanism (EN 50065) in the C-band and stations that wish to transmit must use the

132.5 kHz frequency to inform that the channel is in use [24]. This mandatory protocol defines a maximum channel holding period (1 s), a minimum pause between consecutive transmissions from the same sender (125 ms), and a minimum time for declaring the channel is idle (85 ms). Note that CENELEC specifications regulate only spectrum usage and the CSMA/CA protocol but do not mandate any modulation or coding schemes.

In other countries regulations are different. For example, in the US and Asia the use of up to ~500 kHz is allowed by FCC and ARIB. On the other hand, FCC and ARIB have not assigned specific bands to exclusive use of the utilities so that any device can access the whole 500 kHz and no coexistence protocol is mandated as for the CENELEC C-band.

C. Broadband PLCs

As NB-PLCs started to be progressively successful, BB-PLCs started to appear as well - initially for Internet access applications and successively for HAN and A/V applications. The first wave of interest into the use of BB-PLCs for Internet access started in Europe when Nortel and Norweb Communications in the U.K. announced in 1997 that they had developed a technology to provide access service to residential customers via PLCs [25]. Limited trials of broadband Internet access through PLs were conducted in Manchester and NorWeb prototypes were able to deliver data at rates around 1 Mbps. However, higher than anticipated costs and growing EMC issues caused the early termination of the project in 1999. Other projects in Europe led by Siemens and Ascom encountered a similar fate. On the other hand, a multi-year project funded by the European Community (The Open PLC European Research Alliance, OPERA) led most of the recent research efforts in the field of BB-PLCs for Internet access [26].

Given the disappointing results in using PLCs for Internet access applications, the interest of industry started shifting towards in-home applications in early 2000. In the last decade, several industry alliances were formed with a charter to set technology specification mostly for in-home PLCs, e.g. the HomePlug Powerline Alliance (HPA), Universal Powerline Association (UPA), High Definition Power Line Communication (HD-PLC), and The HomeGrid Forum (HGF). Products allowing PHY data rates of 14 Mbps (HomePlug 1.0), then 85 Mbps (HomePlug Turbo), and then 200 Mbps (HomePlug AV, HD-PLC, UPA) have been progressively available on the market over the past several years. However, none of these technologies are interoperable with each other.

III. The Status of PLC Standardization

A comprehensive and up to date review of PLC standards can be found in [27]. In the next few Sections, we will focus on the latest standardization developments that occurred in both NB and BB-PLCs.

A. Narrowband PLC Standards

One of the first LDR NB-PLC standards ratified is the ANSI/EIA 709.1 standard, also known as LonWorks. Issued by ANSI in 1999, it became an international standard in 2008 (ISO/IEC 14908-1) [28]. This seven layer OSI protocol provides a set of services that allow the application program in a device to send and receive messages from other devices in the network without needing to know the topology of the network or the functions of the other devices. LonWorks transceivers are designed to operate in one of two frequency ranges depending on the end application. When configured for use in electric utility applications, the CENELEC A-band is used, whereas in home/commercial/industrial applications use the C-band. Achievable data rates are in the order of few kbps.

There is today growing interest in HDR NB-PLC solutions operating in the CENELEC/FCC/ARIB bands and are able to provide higher data rates than LDR NB-PLCs. For example, the recent Powerline Related Intelligent Metering Evolution (PRIME) initiative has gained industry support in Europe and has specified an OFDM-based HDR NB-PLC solution operating in the CENELEC-A band, and capable of PHY data rates up to 130 kbps [29]. A similar initiative, G3-PLC, was also recently released [30]. G3-PLC is an OFDM-based PLC specification that supports IPv6 internet-protocol standard, can operates in the $10-490$ kHz band. Recent field trials results of G3-PLC have been reported in [31]. Both PRIME and G3-PLC specifications are open specifications available online.

There are today two approved efforts for the standardization of HDR NB-PLCs, both started in early 2010: ITU-T G.hnem and IEEE 1901.2 [32]. The ITU effort intends to provide a unified recommendation for HAN aspects for energy management integrated with the ITU-T G.hn solution. G.hnem intends to define a HDR NB-PLC technology of very low complexity optimized for energy management applications and address home networking for energy management via wired media. The IEEE 1901.2 project is developing a standard for an HDR NB-PLC technology operating both Alternating (AC) and Direct (DC) Current lines. This standard will support communications through the Medium Voltage (MV)/LV transformer, over MV lines, and over indoor and outdoor LV lines and will support data rates scalable up to 500 kbps depending on the application requirements. The standard will also address grid-to-utility meter, electric vehicle to charging station, and home area networking communications scenarios.

B. The TIA-1113 Standard

The world's first BB-PLC ANSI standard to be approved is the TIA-1113 [33]. The standard is largely based on the HomePlug 1.0 specifications and defines a 14 Mbps PHY based on OFDM [27]. Carriers are modulated with either BPSK or QPSK depending on the channel quality and operational functionality. The Media Access Control (MAC) for HomePlug 1.0 is based on a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme that features an adaptive window size management mechanism in conjunction with four levels of priority [34]. Products based on the TIA-1113/HomePlug 1.0 specifications have experienced a good success in the in-home and industrial markets.

C. The IEEE 1901 Broadband over Power Lines Standard

The IEEE 1901 Working Group was established in 2005 to unify PL technologies with the goal of developing a standard for high-speed ($>$100 Mbps) communication devices using frequencies below 100 MHz and addressing both HAN and access applications [35], [27]. The standard passed the sponsor ballot vote, is now close to ratification and defines two PLC BB technologies: an FFT-OFDM based PHY/MAC and a Wavelet-OFDM based PHY/MAC. The multi-PHY/MAC nature of the IEEE 1901 standard is not a technical necessity but is simply the consequence of a compromise caused by the lack of industry alignment behind a single technology. On the other hand, we can consider the multi-PHY/MAC nature of the IEEE 1901 standard as the first step towards that further consolidation of PLC technologies that will inevitably happen in the future.

The FFT-OFDM IEEE 1901 PHY specification facilitates backward compatibility with devices based on the HomePlug AV specification of the HomePlug Powerline Alliance. Similarly, the Wavelet-OFDM IEEE 1901 PHY specification [36] facilitates backwards compatibility with devices based on the HD-PLC specifications of the HD-PLC Alliance led by Panasonic. Another key component of the proposal is the presence of a mandatory coexistence mechanism called the Inter-System Protocol (ISP) that will allow PLC devices based on the IEEE 1901 standard to share the medium fairly regardless of the PHY differences; furthermore, the ISP will also allow IEEE 1901 devices to coexist with devices based on the ITU-T G.hn standard. The ISP is a new element that is unique to the PL environment - see Sect. III-E.

Devices conforming to the standard must be capable of at least 100 Mbps and must include ISP in their implementation. Mandatory features allow IEEE 1901 devices achieving ~200 Mbps PHY data rates, while the use of optional bandwidth extending above 30 MHz allows achieving somewhat higher data rates. However, data rate improvements due to the use of higher frequencies are often marginal and characterized by short range due to the higher attenuation of the medium and the presence of TV broadcast channels above 80 MHz.

D. The ITU-T G.hn Home Networking Standard

The ITU-T started the G.hn project in 2006 with a goal of developing a worldwide recommendation for a unified HAN transceiver capable of operating over all types of in-home wiring: phone lines, PLs, coax and Cat 5 cables and bit rates up to 1 Gbps [37], [27]. The PHY of G.hn (G.9960) was ratified by the ITU-T in October 2009 while the DLL (G.9961) was ratified in June 2010. The technology targets residential houses and public places, such as small/home offices, Multiple Dwelling Units (MDU) or hotels, and does not address PLC access applications as IEEE 1901 does.

Past approaches emphasized transceiver optimization for a single medium only, i.e. either for PLs (HomePlug, UPA, HD-PLC), or phone lines (HomePNA), or coax cables (MoCA). The approach chosen for G.hn is to design a single transceiver optimized for multiple media. Thus, G.hn transceivers are parameterized so that relevant parameters can be set depending on the wiring type. A parameterized approach allows to some extent optimization on a per media basis to address channel characteristics of different media without necessarily sacrificing modularity and flexibility. G.hn defines several profiles to address applications with significantly different implementation complexity.

The G.hn WG engaged in a year long debate about the selection of the advanced coding scheme. The two competing proposals were based on a Quasi-Cyclic (QC) LDPC code and a Duo Binary Convolutional Turbo Code (DB-CTC). The DB-CTC that was proposed in G.hn was meant to be an improvement over the one specified in the IEEE 1901 FFT-OFDM PHY/HomePlug AV as it allowed a higher level of parallelism and better coding gain. Following the comparative framework suggested by Galli in [38], [39], the G.hn Working Group selected the QC-LDPC code as the only mandatory code in G.hn.

E. PLC Coexistence

PL cables connect LV transformers to a set of individual homes or set of multiple dwelling units without isolation. Hence, they are a shared medium (like coax and wireless) and do not provide links dedicated exclusively to a particular subscriber. The signals generated within the premises interfere among each other, and with signals generated outside the premises. As the interference increases, both from indoors and outdoors sources, PLC-based Smart Grid terminals will experience a decrease in data rate as packet collisions increase, or even complete service interruption. In short, PLCs are interference limited, and have a relatively small spectrum available for FDM. For this reason, it is necessary to devise mechanisms to limit the harmful interference caused by non-interoperable neighboring devices. Similar considerations can be made about the interference limited nature of many wireless networks, e.g. WiFi, WiMAX, Zigbee, Bluetooth, etc.

It is also important to ensure coexistence between Smart Grid and In Home BB technologies, since the former have traditionally a much longer obsolescence horizon than the latter. It is likely that the number of homes fitted with energy metering and control devices that utilize Smart Grid technology will dramatically increase in the near future. On the other hand, in Home BB technology continuously evolves, improving the transmission rate. The adoption of a coexistence mechanism will enable continued and efficient operation of Smart Grid devices in the presence of newly-deployed In Home BB devices.

The issue of PLC coexistence was first raised two decades ago in CENELEC. Since CENELEC does not mandate PHY/MAC recommendations, it was necessary to provide a fair channel access mechanism that avoided channel capture and collisions when non-interoperable devices operated on the same wires. In fact, if non-interoperable devices access the medium, then native CSMA and virtual carrier sensing do not work and a common mechanism must be defined. CENELEC mandates a CSMA/CA mechanism only for the C-band [24] where a single frequency (132.5 kHz) is used to inform that the channel is in use. An extension of this method that utilizes three or four channel-in-use frequencies for HDR NB technologies operating in the the FCC band is now being discussed within the Priority Action Plan (PAP-15) created by the US National Institute of Standards and Technology (NIST) to address PLC coexistence issues [40].

Another approach to coexistence was introduced by the HomePlug Powerline Alliance to solve the issue of non-interoperability between HomePlug 1.0 and the newer HomePlug AV stations. The HomePlug *hybrid delimiter* approach allows HomePlug AV/IEEE 1901 FFT-OFDM PHY stations to coexist with HomePlug 1.0 (TIA-1113) stations by prepending to their native frame the HomePlug 1.0/TIA-1113 delimiter. This allows stations to correctly implement CSMA/CA and virtual carrier sensing.

The hybrid delimiter approach is a CSMA-based coexistence mechanism and, thus, does not eliminate interference caused by non-interoperable stations and cannot guarantee QoS when the traffic of at least one of the coexisting schemes grows. Furthermore, the priority based QoS mechanism shared by HomePlug 1.0 and HomePlug AV/IEEE 1901 FFT-OFDM has been recently shown to be ineffective [41]. The use of hybrid delimiters is a somewhat inefficient approach if multiple technologies are to coexist as it would be necessary to pre-pend multiple delimiters (one for every non-interoperable technology) with increasing loss in efficiency. The HomePlug hybrid delimiter method also exhibits security weaknesses as it is not a mechanism based on *fair sharing*. In fact, HPAV/IEEE 1901 FFT-OFDM PHY can defer indefinitely HomePlug 1.0 (TIA-1113) stations from accessing the medium so that, while HomePlug 1.0 (TIA-1113) stations cease all transmissions, HPAV/IEEE 1901 FFT-OFDM PHY stations remain the only active ones on the medium. This capability may raise security concerns since HPAV/IEEE 1901 FFT-OFDM PHY stations (either legitimate or rogue) can stop from working Smart Grid devices based on HomePlug 1.0 (TIA-1113).

Except for the CSMA mechanisms described above, the issue of coexistence between PLC devices has been rarely addressed in the technical literature and the first published paper dates back only few years [42], [43], [44]. The Consumer Electronics Powerline Alliance (CEPCA) has been developing together with the Universal Powerline Alliance (UPA) a general coexistence protocol (CXP) for BB-PLC devices. This CXP mechanism is now included as an option in the IEEE 1901 Draft standard.

For the specific case of coexistence between the two IEEE 1901 PHYs, Panasonic proposed to the 1901 WG a novel coexistence mechanism called the Inter-PHY Protocol (IPP) [45]. The IPP was designed to ensure compatibility with the general CXP mechanism developed by CEPCA/UPA but it was less complex than CXP, it allowed some distributed features, and also allowed devices to perform Time Slot Reuse (TSR)[3]. Although the IPP was originally designed to enable efficient resource sharing between devices equipped with either the Wavelet-OFDM or the FFT-OFDM PHYs in IEEE P1901, it was soon recognized that the IPP was also an excellent tool for regulating simultaneous access to the PL channel of both 1901 and non-1901 devices, e.g. the ones based on the ITU-T G.hn standard. Panasonic modified the IPP originally conceived to extend coexistence to G.hn devices and proposed this enhanced mechanism called Inter-System protocol (ISP) to both ITU-T and IEEE. The ISP is now a mandatory part of the IEEE 1901 Draft (Chapter 16) and is also specified in ITU-T Recommendation G.9972 which has been ratified by the ITU-T in June 2010. The approach followed in the design of the IPP/ISP is a radical conceptual departure from previous designs in CENELEC and in HomePlug which are both based on CSMA. Thus, none of the drawbacks mentioned above are present in the ISP [45].

[3] TSR is the capability of nodes to detect when it is possible to transmit simultaneously to other nodes in neighboring systems, without causing harmful interference - see [45] and [46] for more details

IV. The Role of Communications in the Smart Grid

The history of communications through PLs shows that the power infrastructure is much more than the sum of its physical components. It is already a large scale cyber-physical system, where the physical system is coupled with a communication and computing network, in part aimed at controlling the automation aspects of the system, in part allowing the interaction and feedback of socio-economic networks through the energy market [47]. Initially, the electric system was composed of multiple but isolated generation plants. Recognizing that the interconnection between systems could provide higher profitability thanks to the access to a wider set of resources, the electric system was gradually transformed into an interconnected grid becoming the large scale cyber-physical system we know today. This transformation also introduced redundancy in case of equipment failure or unexpected demand fluctuations.

A. Today's SCADA and Beyond

The cyber infrastructure model that supports the management of the power network today is referred to as the Supervisory Control and Data Acquisition (SCADA) model. A system conforming to the SCADA model usually comprises the following components: a Human-Machine Interface (HMI), a supervisory SCADA Master server, a set of Remote Terminal Units (RTUs) and/or Programmable Logic Controller, sets of Intelligent Electronic Devices (IEDs), and the supportive communication infrastructure that furnishes the communications between the supervisory Master and the RTUs and between the RTUs and IEDs. The IEDs usually include various types of microprocessor-based controllers of power system equipment, such as circuit breakers, transformers, and capacitor banks. Multiple SCADA systems are today deployed within a plant and even at a substation. Thus, there is not a single SCADA network and some are based on Ethernet/IP and some are not.

The network support for SCADA has traditionally used combinations of wireless radio links, dial-up leased lines and direct serial or modem connections to meet communication requirements, although Ethernet and IP over SONET/SDH are more frequently used at supervisory control center or large substations. Although there is no single system, a two-level tree topology is very common to all communication networks supporting SCADA operations. Figure 1 shows the RTUs at the intermediate level, sending control signals released by the supervisory master to the IEDs and gathering the measurement information from IEDs to the supervisory master. Although newer substation automation systems are able to handle data generated at a faster pace, communications links between the RTUs and control center are often inadequate to handle an increasing volume of data [11].

The SCADA centralized monitoring model is aimed at feeding data that constantly update the state estimation and system identification at the level of control stations, which assist the power system operator in his effort to adjust and/or optimize the power system operation and make sure that the system operational condition is a stable point for the system. The key problem of the SCADA model is, and has always been, the lack of architectural considerations on its latency, and what archetype for the information gathering would be needed to contain it. Furthermore, in SCADA, most of the sensors capture and deliver measurements asynchronously. Hence, with SCADA the physical response of the system to contingencies cannot be optimally controlled in real time. In addition to the existing SCADA control, there are local feedback mechanisms in place such as generator excitation control (GEC), automatic governor control (AGC), automatic voltage regulator (AVR), HVDC control, etc.

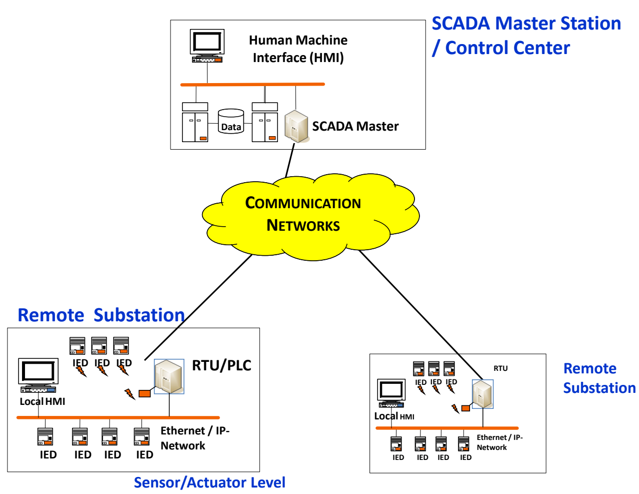

Fig. 1. A Power Grid SCADA system.

New transducers such as the synchrophasors or Phasor Measurement Units (PMUs) are being today deployed in the transmission side of the grid. PMUs can provide precise grid measurements of AC voltages and currents at high speed (typically 30 observations per second compared to one every 4 seconds using conventional technology). Each measurement is time-stamped according to a common time reference, which utilizes the global positioning system (GPS) signal and has an accuracy better than 1 μs. Based on these measurements, improved state estimation can be derived so that it is possible to measure the state of a large interconnected power system. The immediate consequence of PMU deployment is that a large amount of data is being generated and the networking provisions for delivering this amount of data at the required QoS are not in place yet. The Wide Area Measurement Systems (WAMS) utilize a *back-bone* phasor network which consists of phasor measurement units (PMUs) dispersed throughout the transmission system, Phasor Data Concentrators (PDC) to collect the information and a SCADA master system at the central control facility. At the central control facility, system wide data on all generators and substations in the system are collected every 2 to 10 seconds.

1) Flexible AC Transmission System (FACTS): The FACTS is composed of power electronics and other equipment that provides control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability of the network. FACTS control based on PMU can potentially be implemented as an effective wide area control means to mitigate sub-synchronous oscillations. This brings challenges to current SCADA/WAMS systems as measurements must be interoperable, consistent, and meet the real time requirement of fast transient and voltage stability control.

Distributed FACTS devices are smaller in size and less expensive in costs than traditional FACTS devices which may make them better candidates for wide scale deployment so that the topic of distributed control has been receiving increasing attention [48], [49], [50], [51]. Some researchers have also proposed that the control for D-FACTS devices could be decentralized as today more devices are equipped with fast communication capabilities and this scheme may help bypass the latency problem caused by the centralized monitoring and control implementation.

2) Smart Grid in the Distribution Network: Besides the increase in the data volume being generated within the transmission network for monitoring and control, there is another fundamental driver that will require a *smarter* grid: the emergence of an increasingly dynamic and complex distribution side of the grid. The realization of an AMI, the integration of RES and other DERs, and the new goals for improving distribution automation will produce radical changes in the distribution network. As a consequence, PMUs may soon find a role also in the state estimation of this new and dynamic distribution grid because of the higher level of uncertainty due to the integration of time-varying DERs and distributed control mechanisms.

The creation of a pervasive AMI has polarized considerable attention as many advocate the AMI network as being the core sensing and measurement system of the distribution network. Most proposed AMI architectures include a data hub or concentrator service where measurement data from smart meters will first be collected and unified before being further sent to the back office of the utility. Since this centralized model does not scale, it is reasonable to look at alternative architectures that have greater parallelism in designing the next generation cyber system. The availability of scalable networking alternatives as well as decentralized and fully automated processing will allow connecting the embedded intelligence in the system in a way that will support each of the physical devices with real time feedback from its neighboring devices. This is a profound paradigm shift from current remedial practices that merely change generator settings thus effecting everything downstream rather than a particular portion of the grid that has a problem. Going forward it will be necessary to understand Volt/VAr not only at a macro level but also at micro level over each segment of the grid.

B. Control and Sensing for Cyber-Physical Systems

The grid is a complex cyber-physical infrastructure composed of a maze of interdependent and interacting parts. The cyber-physical system can be seen as pair of partner networks: a physical network over which energy flows and the cyber system (including a wide area network of sensors and data sinks that compute and relay information to actuation sites). The service provided is energy delivery from sources to destination and, in principle, nothing else but the physical network is required. If a physical part of the system fails, the safe operational limits for the network may change. Hence, the timely notification of failures is critical and, as failures spread, the network will face a sudden surge in highly correlated sensor traffic similar to a broadcast storm [52]. Effectively the sensors are reporting the same event, however in doing so they will compete for network resources, causing congestion.

The SCADA model leaves a great deal of control to the human operator in the loop. Can one develop a fully automated solution? As Witsenhausen's counterexample indicated, the separation of estimation and controller design fails to hold even in the simplest settings [53]. Many theories are emerging that deal with the issue of control under communication constraints that apply broadly to cyber-physical systems (see e.g. [54], [55], [56], [57], [58]), however modular and scalable solutions of network control are still elusive in many cases. These technical obstacles are especially relevant when a separation of time scales is impossible. Unlike transportation, water network and other commodities that are encountered in large scale supply chains, electrical power moves just as fast as communication signals do. Therefore, both the physical network dynamics and the cyber system data spread at comparable speeds, exacerbating the difficulties of decoupling communications from control and management.

Part of the the difficulty in the optimization of concurrent controllers is that each controller can infer information about unobservable events not only by pooling sensors information but also by observing the other controllers actions [59]. However, in some important cases the controllability of a discrete event system is undecidable [60].

Recently, the low cost of communication and computation devices has determined a considerable pressure to grow these networks in size and complexity. Sensor networking research has flourished in the past ten years [61] and new generations of sensors communications are being standardized at a fast pace especially in the wireless field - e.g., see IETF 6LoWPAN, IEEE 802.15.4, IEEE 1451, etc. PLC standards are emerging with similar functionalities, as discussed in Section V. Remarkably, this process has reversed completely the natural order of design, where the information network infrastructures, routing and clustering primitives are chosen from rather generic sensor networking models that are not delay sensitive nor specifically tied to energy distribution specifically, thus dictating ultimately the delays that the control needs to work with, not the other-way around.

It is therefore likely that this first generation of devices, networks, data processing and software agents will be over-designed in many ways and also lacking in other aspects that are today unforeseen. This will create incentives in designing a new generation of optimized devices and protocols tailored to the actual Smart Grid needs. Some important elements that these new solutions will have to incorporate are considered in the following subsections.

1) Grid Control Aspects: The voltage on the mains is a narrow bandpass signal, around the mains frequency $f_0 = 60$ or 50 Hz. The complex phasor vectors V and I

$$\begin{aligned} V &= \mathrm{V}\angle V \\ I &= \mathrm{I}\ \angle I, \end{aligned} \tag{1}$$

represent the sinusoids of instantaneous vector voltage $v(t)$ and injected vector current $i(t)$ respectively, around f_0:

$$\begin{aligned} v(t) &= \sqrt{2}\mathrm{V}\cos(2\pi f_0 t + \angle V), \\ i(t) &= \sqrt{2}\ \mathrm{I}\cos(2\pi f_0 t + \angle I). \end{aligned} \tag{2}$$

In the NB regime the power network dynamics are coupled by the algebraic equation

$$YV = I, \tag{3}$$

where Y is the matrix of network admittances at frequency equal to f_0, which is determined not only by the connecting topology but also its electrical parameters. The relationship in (3) is valid because the variations of $Y(f)$ over the spectrum of $v(t)$ are negligible. Given a network with n nodes and m links (which may also be referred to as "buses and branches (or lines)" in power grid analysis; or "vertices and edges" in graph theory and network analysis), each link $l = (i, k)$ between nodes i and k has a line impedance at 60 Hz $z_{pr}(l) = r(l) + jx(l)$, where $r(l)$ is the resistance and $x(l)$ the reactance. Usually, for HV transmission network, the reactance dominates. The $n \times n$ network admittance matrix Y is

$$Y = A^T diag(\mathbf{y_{pr}})A \tag{4}$$

where $\mathbf{y_{pr}}$ is the line admittance vector, whose elements are $y_{pr}(l) = 1/z_{pr}(l)$, and A is the line-node incidence matrix. Each bus corresponds to a certain power flow injected (generator bus) or absorbed (load bus), or it simply represents an intermediate bus. The instantaneous power at each bus is given by $p(t) = v(t) \odot i(t)$, where $\odot$ means vector element-wise multiplication. Taking the phasor value, we have the network power flow equation as

$$S = V \odot I^*, \tag{5}$$

where $(\cdot)^*$ indicates complex conjugation, and $S = P + jQ$ is the vector of injected complex power

$$\begin{aligned} P &= \mathrm{Re}(V \odot I^*) = \mathrm{VI}\cos(\angle V - \angle I) \\ Q &= \mathrm{Im}(V \odot I^*) = \mathrm{VI}\sin(\angle V - \angle I). \end{aligned} \tag{6}$$

where P is the *real power* or *active power*, which is equal to the DC component of the instantaneous power $p(t)$; whereas Q is the *reactive power* which corresponds to the $2f_0$ sinusoid component in $p(t)$ with zero average and magnitude Q.

A set of basic constraints needs to be satisfied for enforcing stability in the power grid: (a) the network power flow must be balanced; (b) the input power for generation or loads adjustment or power injects from other kinds of sources must have strict operational ranges; (c) voltage must take acceptable levels; (d) line thermal limits must be enforced, i.e. line current should keep its magnitude below a specified limit; (e) stability condition must be satisfied, i.e., the Jacobian matrix $J(V)$ of the network power flow equations must have negative real parts which keep a safe distance from zero.

Mathematically the conditions described above can be written as follows[4]:

$$\begin{array}{ll} (a) & S = V \odot (YV)^* \\ (b) & S_{\min} \leq S \leq S_{\max} \\ (c) & \mathrm{V}_{\min} \leq \|V\| \leq \mathrm{V}_{\max} \\ (d) & \|diag(\mathbf{y_{pr}})AV\| \leq \mathrm{I}_{\max}^{line} \\ (e) & \mathrm{Re}\,(eig(J(V))) \leq -\varepsilon \end{array} \quad (7)$$

where the Jacobian matrix $J(V)$ of the network power flow equations is defined as follows:

$$J(V) = \begin{bmatrix} \frac{\partial P}{\partial \angle V} & \frac{\partial P}{\partial \|V\|} \\ \frac{\partial Q}{\partial \angle V} & \frac{\partial Q}{\partial \|V\|} \end{bmatrix}. \quad (8)$$

The key feedback mechanisms consist in controlling the elements of S, by increasing supply or shedding loads, or controlling Y by switching parts of the infrastructure or utilizing FACTS. In this case the monitoring needs to be synchronous; polling each part of the network and gathering centrally all the data, and then distributing the control signal is a solution that is not scalable and may result in congestion.

2) Traffic Generated by the Physical System: There is a universal brute force solution to congestion problems: increase the service rate so intermediate nodes buffers never grow. In so doing, network bottlenecks will not constitute a problem since over-provisioned nodes will push through the messages received in face of the worst conditions. There is clearly merit in this view of the problem, as technology that offers high rates becomes cheaper and one does not need to explore new networking concepts to design Smart Grid. The approach of over-provisioning would certainly help both the infrastructure monitoring as well as the wide area control, but of course entails a high cost in provisioning high capacity links.

An alternative view that has emerged in the sensor networking community is to exploit directly the data structure and correlation among the sensor data to reduce the information flows and to manage the rise in complexity of routing and processing data [62], [63], [64], [65], [66], [67]. In fact, eliminating queuing delays only may be insufficient since the brute force solution of polling all the sensors can become the true bottleneck for the sheer problem of collecting all the data in a timely way from the sensors.

[4] Note that S, V, and Y are time-varying variables, since their magnitude and/or phase angles are changing with system operating status. Here we omit the "(t)" term only for notation conciseness.

Modeling the traffic of phase sensors in the electrical network is an important research direction. Network scientific work on the power network infrastructure has so far been focused on capturing topological characteristics, and studying vulnerability to topological changes. The models by Watts and Strogatz (1998) [68], Newman (2003) [69], Whitney and Alderson (2006), fall in this class. Understanding the data source amounts to taking a more thorough approach to modeling than done thus far. Building on this prior work, we have developed a model that captures accurately both topological and electrical characteristics of the power grid and models.

The interesting and peculiar aspects of a PLC based Smart Grid is that the communication graph will be a subgraph of the physical infrastructure devoted to power delivery. The same network scientific analysis carried out to analyze the grid can then be utilized also to provide insights on the network coverage of a PLC based Smart Grid system. This fact is an opportunity as well as a challenge that requires empowering the distribution network with PMUs to allow continuous monitoring of channel and network states and provide information on the physical state of the distribution system.

3) Cooperative Schemes for PLC Networks: Naive solutions based on polling (see IEEE 1901 Draft, Chapter 8) simply do not scale. Given its wide geographical area of deployment, the Smart Grid will utilize relays potentially at a massive scale. It is well known that interference can lead to vanishing throughput as the size of the network scales up, as shown in [70] for the case of wireless networks. PLC are likely to be equally challenged due to the fact that relays interfere with each other. This complicates greatly routing decisions. In general, routing itself will also need to be flexible; it is, in fact, critical to equip the network with scalable primitives for self-organization that would allow the network to find rapidly alternative paths to deliver sensitive information, in light of local failures.

One especially problematic operation when using relays in broadcast media is, paradoxically, broadcasting (or multicasting). To use decentralized storage, control microgrids and taper off the demand as a means to compensate for volatility of supply, broadcast control signals will very often flow through the network. Delivering in a timely fashion to large populations of Smart Grid terminals these messages through many relays will produce a broadcast storm if protocols to support this function are not designed judiciously [52]. Failures in the infrastructure are likely to generate a similar storm of signals, due to cascading effects that impact close by elements of the system. The classical solution to this problem at the network layer is either forming a static routing table that resolves such conflicts (this takes time and is not robust), or resorting to the so-called called probabilistic routing [52]. Interestingly, these functions can be greatly improved upon by using physical layer cooperation in forwarding the signal. Cooperation is a physical layer solution to the relay problem, that allows signals to be superimposed in the time and frequency dimension by appropriately encoding as well as timing the signals transmitted by populations of relays.

This concept has been independently introduced for wireless networks and for PLC networks in [71] and [72], respectively. The first working implementation of a cooperative PLC-based AMR system using HDR NB-PLC was realized under the REMPLI project (Real-time Energy Management via Power lines and Internet) [73], [74]. The REMPLI project has experimentally demonstrated the possibility of using HDR NB-PLCs in transforming channel contention into channel *cooperation* by using a Single Frequency Network with flooding based routing. The advantage of these approaches is that the delivery of the message can be predicted much more accurately and the transmission is more power efficient.

V. The Role of PLCs in the Smart Grid

There are many examples of applications where PLCs are used for utility applications. Although these applications span the whole grid from transmission to distribution, PLC technology is today more mature when operating on the distribution side. In the next subsections, we will review the salient applications of PLCs for the Smart Grid at all voltage levels.

A. PLCs for High Voltage (HV) Networks

Although the greatest transformation from today's grid to tomorrow's Smart Grid is expected to take place mostly on the distribution side, also the transmission side will have to undergo progressive changes which some believe will be slower than for the distribution side and will also occur at an evolutionary pace [75]. The availability of a reliable communication network on the transmission side is critical for the support of several applications such as state estimation (PMU over WAMS), protective relaying, SCADA expansion to remote stations, and remote station surveillance.

Traditional communications technologies for the HV network are based on either fiber optical or microwave links, but there is recent growing interest in the use of PLCs as a potential candidate. HV lines are decent waveguides as channel attenuation characteristics show a benign pass-band and time-invariant behavior. The noise is mainly caused by corona effect and other leakage or discharge events, and corona noise power fluctuations of some tens of dB can be observed due to climatic dependency. Compared to LV/MV lines, HV are a better communications medium characterized by much lower attenuation.

The feasibility of sending PLC signals over HV lines has been reported recently by the US Department of Energy, American Electric Power (AEP), and Amperion, who jointly tested successfully a PLC link over a 69 kV and 8 km long line with no repeaters [76]. Data rates of 10 Mbps with latency of about 5 ms were reported while complying with FCC emission limits. Next steps for this project is to raise the applicable voltage to 138 kV and also extend the repeater-less distance. Other international activities involving PLC over HV lines can be found in [77], [78], [79].

Besides for providing connectivity on the transmission side, PLC over HV lines is also being considered for remote fault detection. For example, successful experiments were recently reported for the detection of broken insulator, insulator short circuit, cable rupture, and circuit breaker opening and closing [80]. In another example, PLC over HV appears to be also useful in determining the change in the average height above ground of horizontal HV overhead conductors. Authors in [81] report successful testing on a 400 kV overhead HV line of a real-time sag monitoring system based on PLCs in the 50-500 kHz band.

At this time, it is possible to express only cautious optimism about the use of PLCs in the transmission side as further testing is certainly needed. On the other hand, the increasing interest in PLC over HV lines is somewhat confirmed by the fact that the IEC-TC57/WG20 started a couple of years ago to work on updating the obsolete PLC standard IEC 60495 to include digital PLC for HV.

B. PLCs for Medium Voltage (MV) Networks

An important requirement for future Smart Grids is the capability of transferring data concerning the status of the MV grid where information about state of equipment and power flow conditions must be transferred between substations within the grid. Traditionally, substations at the MV level are not equipped with communications capabilities so the use of the existing PL infrastructure represents an appealing alternative to the installation of new communications links. Some substation automation functions need the substation IEDs to communicate with external IEDs. In the case of fault location, fault isolation and service restoration then substation IEDs must communicate with external IEDs such as switches, reclosers, or sectionalizers. In another example, implementation of voltage dispatch on the distribution system requires communications between substation IEDs and distribution feeder IEDs served by the substation. All these communications require low-speed connectivity that is well within PLC capabilities.

A large portion of MV equipment in the world has been installed more than 40 years ago. Fault detection as well as monitoring for ensuring longer lifespan to critical cable connections is then becoming a true operational, safety and economical necessity. Most techniques used today include on-site expensive truck rolls; for example, available power cable diagnostics are based today on partial discharge measurements (typically based on Time Domain Reflectometry) on temporally disconnected connections which are externally energized. From an operational point of view online diagnostic tools are preferable and soon will become the main trend [82]. The coupling of PLC signals up to 95 kHz (European CENELEC A-band) for online diagnostic data transfer over MV cables is studied in [83] where the authors also emphasize the advantage of integrating diagnostics tools that serve the dual purpose of sensing and communication devices.

DG systems can supply unintentional system islands isolated from the remainder of the network. It is important to quickly detect these events, but passive protections based on traditional measures may fail in island detection under particular system-operating condition. The use of LDR NB-PLCs (CENELEC A-band) for injecting a signal in the MV system has been analyzed and tested in [84], and it appears to be less expensive compared to other methods based on telephone cable signals. A similar approach has been investigated in [85] for the prevention of islanding in grid-connected photovoltaic (PV) systems and it was found that PLC-based "*islanding prevention offers superior islanding prevention over any other existing method*." Other applications of PLCs within the area of DG can also be found in [86].

In addition to remote control for the prevention of the islanding phenomenon, other applications related to monitoring on the MV side (temperature measurement of oil transformers, voltage measurement on the secondary winding of HV/MV transformers, fault surveys, power quality measurement) have also been discussed and analyzed [87].

C. PLCs for Low Voltage (LV) Networks

Most PLC Smart Grid applications on the LV side are in the area of AMR/AMI, vehicle-to-grid communications, DSM, and in-home energy management.

1) Automatic Meter Reading and Advanced Metering Infrastructure: In addition to basic meter reading (AMR), AMI systems provide two-way communications that can be used to exchange information with customer devices and systems. Furthermore, AMI enables utilities to interact with meters and allows customer awareness of electricity pricing on a real-time basis [47]. Although smart meter deployment is getting today a lot of attention worldwide, a smart meter is not really a necessary part of the Smart Grid as there are several alternative ways to implement Smart Grid applications without smart meters. On the other hand, smart meters are important tools for the utilities to reduce their operational costs and losses because they provide capabilities that go beyond simple AMR, e.g. remote connect/disconnet and reduction of energy theft.

PLC technology is certainly well suited for AMR/AMI. There is a vast amount of field data about the performance of PLC-based smart meters as over 100 million UNB/NB-PLC devices have been deployed around the world. As mentioned in Sect. II-B, UNB-PLC devices were the first to be used for AMR/AMI. Although UNB systems are characterized by extremely low data rates (~1-2 bit per hour for the Turtle System and ~60 bps for TWACS), PLC signals in the ULF band propagate easily through several MV and LV transformers. Furthermore, UNB-PLC do not require any kind of PL conditioning as other PLC technologies operating at higher frequency would often require due to the low pass effect of shunt power factor correction capacitors and series impedances of distribution transformers. As a consequence, these systems are able to cover very large distances (150 km or more).

In the last couple of decades, UNB-PLC system have experienced growing success in the market and some tens of millions of meters have been deployed by hundreds of utilities. The Turtle System has found good applicability in those areas served by US rural cooperatives since they are characterized by low population density and wide geographical spread. TWACS has been deployed both by rural cooperatives and large investor-owned utilities.

Also NB-PLC technologies are gaining a lot of interest for AMI applications, an interest exemplified by the recent creation of two projects devoted to the standardization of HDR NB-PLC transceivers (IEEE 1901.2 and ITU-T G.hnem). The capability of HDR NB-PLC of delivering substantially higher data rates with respect to UNB-PLC comes at the price of reduced range and, sometimes, transformer conditioning. Although there are recent reports that confirm the existence of narrowband windows of low attenuation in MV/LV transformers [31], [88], it is difficult to draw at this time general conclusions on this matter since there is no statistical model that allows a more quantitative assessment of the capability of PLC signals to pass distribution transformer. Furthermore, not all PLC technologies offer the same reliability and often this capability strongly depends on the transformer itself. Specifically, BB-PLC signals do not pass the distribution transformer and necessarily require the installation of coupling units to by-pass it; NB-PLC technologies may in some cases pass the transformer - although with an SNR hit of some tens of dB.

The architectural consequence of MV/LV connectivity is that many more meters would be handled by a single concentrator located on the MV side. This concentrator node would then send the aggregated data from many meters back to the utility using either PLC or any other networking technology available in situ. This capability also heavily impacts the business case when there is a very different number of customers per MV/LV transformer: in North America, the majority of transformers serves less than 10 customers; in Europe, the majority of transformers serves 200 customers or more. Thus, especially in the US, it is economically advantageous to avoid coupler installation and resort to technologies that allow connectivity across the distribution transformer.

In emergency situations it is often the case that conventional networking technologies encounter congestion due to a spike in the collision rate, i.e. when all meters tend to access the channel at the same time (blackout, restoration, etc.) or when multiple DR signals requiring immediate action are sent to households. In these challenging scenarios, traditional networking approaches including wireless sensor networks fail due to the network congestion and competitive channel access mechanism. Unlike wireless solutions based on ZigBee or WiFi, PLC-based AMI have a proven track record of being able to avoid network congestion when cooperative schemes are employed - see the REMPLI project [73], [74].

2) Vehicle-to-Grid Communications: A PHEV charges its battery when connected to an Electric Vehicle Supply Equipment (EVSE) which, in turn, is connected to premises wiring or to distribution cables (airport, parking lots, etc.). A variety of applications scenarios can be envisioned in enabling a communication link between the PHEV and the utility, e.g. for the control of the localized peak load that the increasing penetration of PHEVs would inevitably create. The availability of a communication link between the car and the EVSE (and even beyond the EVSE to the meter, the Internet, the HAN, the appliances, the utility, etc.) will be the key enabler for these applications.

The first distinctive advantage of PLCs for vehicle-to-grid communications is the fact that a unambiguous physical association between the vehicle and a specific EVSE can be established, and this is something that is not possible to accomplish with wireless solution even if short range. This physical association has advantages, especially in terms of security and authentication. Although PLC communications for this scenario is impaired by several harmonics present due to the inverter, there are today several ongoing tests on both BB-PLC and NB-PLC solutions within the "PLC Competition" being conducted by the Society of Automotive Engineers (SAE). In terms of cost and worldwide regulations NB-PLC solutions are currently considered the preferred choice with respect to BB-PLC. Since NB-PLC are also excellent choices for meters and appliances, the availability of a single class of PLC technologies for the inter-networking of different actors in the same applications is of course tempting.

3) Demand Side Management (DSM): Demand Response (DR) is one of the primary DSM applications on the LV side and has been receiving growing interest, especially in the US [12], [13]. DR refers to the ability to make demand able to respond to the varying supply of generation that cannot be scheduled deterministically, e.g. solar and wind. Thus, DR is a means to alleviate peak demand and to bring more awareness on energy usage to the consumer [47]. It is believed that DR will allow a better control of peak power conditions, maximize the use of available power, increase power system efficiency through dynamic pricing models, and allow customers to participate more actively to energy efficiency. Implementation of DR requires establishing a link (either direct or indirect, e.g. via a gateway in the home) between the utility and household appliances.

The largest direct load control system in the world has been operating in Florida for over twenty years using a UNB-PLC technology (TWACS). Florida Power and Light manages via TWACS over 800,000 Load Control Transponders installed at the premises of over 700,000 customers and can shed up to 2 GW of load in a matter of a few minutes. TWACS serves the dual role of load control and AMR. It is interesting to verify that such a large scale direct control system can operate successfully using a two-way communication system that delivers only few tens of bps.

Due to the higher attenuation that PLC signals experience over the LV side, BB-PLC solutions may not always be ideal for DR applications when direct load control is implemented since the distance between appliances and the utility signal injection point (the smart meter, the MV/LV transformer) may be in some cases too large. On the other hand, when DR is implemented with indirect control via a gateway, e.g. a Home Energy Management System (HEMS), then BB-PLC solutions are technically adequate and would provide the added benefit of being able to transfer securely data from Smart Grid applications to the HAN and vice versa. Although technically adequate, other considerations related to cost may arise as BB-PLCs technologies may be overly-dimensioned for carrying out DR. Due to the much lower path loss at lower frequencies, NB-PLC solutions are also good candidates for DR applications for both direct and indirect load control.

4) In-Home Environment: There are intriguing possibilities of tying Smart Grid applications with HEMS, and there is a strong belief that these application will help foster a behavioral change in how consumers address energy consumption. The home is a natural multi-protocol and multi-vendor environment and it is unrealistic that this will change anytime soon even though there is a lot of pressure by some industry segments to reduce the number of allowed networking choices. A variety of BB-PLC solutions will continue to be installed by consumers regardless of any convergence in the networking choices for the Smart Grid. From this point of view, segregating Smart Grid applications in one band (CENELEC/FCC/ARIB) and separating them from traditional entertainment and Internet access ones running on BB-PLCs (but also with the capability of bridging these applications them via the HEMS) seems a good engineering solution that balances efficiently the various requirements of these very different set of applications.

Although a HEMS does not really provide compelling financial benefits to residential customers, it can yield substantial benefits to utilities in terms of improving grid reliability and demand forecasting as well as reducing peak demand. In fact, a HEMS can serve the function of "sensor" in a much more complete and effective way than what a smart meters would be capable of doing. While smart meters can only report instantaneous demand, a HEMS could actually report to the utility (or third party energy service provider) the forecasted demand of energy. The forecast capability of a HEMS could be very accurate as it would be based on the "state" of the home and on the behaviorial model built on consumer activity throughout years. The state of the home tracked by a HEMS could include: the present and predicted energy demand of an appliance as it goes though its service cycle, storage levels of batteries, amount of consumer shifted demand (service queue), etc. If a utility had at its disposal the knowledge of the state of every home (or of a set of homes or microgrids via aggregators), forecasting and scheduling of generation and DSM would be possible with more relaxed communications requirements. Furthermore, storage levels and queued demand could also become part of pricing models.

We also point out that today there is a growing interest in hybrid AC/DC wiring infrastructure. Within the home, the development of a DC infrastructure yields great benefits to energy generation (photovoltaic, fuel cell) and storage (rechargeable battery). Both NB and BB-PLCs greatly benefit from operating over DC lines as the channel is time-invariant and appliance cyclostationary noise disappears - with the exception of impulsive noise caused but AC/DC inverters.

D. What PLC Technology Fits Best Smart Grid Applications?

Both NB and BB-PLC solutions can find their space of application and the choice of which PLC technology best fits the application scenario will depend not only on technical matters but also on regulatory and business case aspects. In fact, regulations on allowed emissions levels and available frequencies can make us reach different conclusions on what PLC technology is preferable for a given scenario. For example, FCC Part 15 in the US allows the use of both NB and BB-PLC technologies in outdoor deployments; in the EU, on the other hand, BB-PLC solutions may not be practical because of stricter regulations that limit the allowable transmit power and, as a consequence, would require smaller repeater spacing and thus increased deployment costs. The use of BB-PLC solutions outdoor is also forbidden in some countries, e.g. Japan, in which case only NB-PLC solutions would be available for Smart Grid applications.

One compelling advantage of using PLCs is that the traditionally separated functions of sensing and communicating blur together and thus a PLC transceiver could be designed to switch between functioning as a "sensor" and as a communications device. This capability may have applications in Power Quality (PQ) which is an important concern for utilities because of the value of predicting and avoiding electric disturbances [89].

Another advantage of using existing PLs as a communications channel is that utility applications almost always require redundancy in protection and control applications, and the need for redundancy should also be extended to the availability of redundant communications channels [90]. From this point of view, the availability of an existing wired infrastructure greatly reduces the cost of deploying a redundant communication channel. Of course, the cost savings of having the infrastructure available should be weighed against the cost of deployment of repeaters and couplers. Though it is hard to give universal values since the range depends on the environment (overhead or underground cables, type of cables, loading conditions, etc.), typical average values of path loss for PLCs in terms of dB/km are given in Table I - see for example [91], [92]. As Table I suggests, the use of BB-PLCs over LV networks can entail very small repeater spacing due to the high path loss whereas larger repeater spacing can be tolerated over MV networks, especially for the overhead case. Due to the wide variability of scenarios, PLC may be a good solution or not and its appropriateness must be assessed on a case-by-case basis - just as one would do for any other networking technology.

TABLE I
TYPICAL PATH LOSS RANGES FOR PLCS IN DB/KM. VALUES VARY DEPENDING ON CABLE TYPE. OH: OVERHEAD; UG: UNDERGROUND.

	$f = 100$ kHz	$f = 10$ MHz
Low Voltage	1.5-3	160-200
Medium Voltage (OH)	0.5-1	30-50
Medium Voltage (UG)	1-2	50-80

NB-PLCs have several advantages when compared to BB-PLCs when AMR or DR applications involving appliance control are considered - even when NB-PLC solutions are compared with scaled down versions (low complexity, low power, low data rate) of BB-PLC solutions[5]. Below, we summarize the main reasons behind this preference:

- *Ease of upgrade to future versions*: NB-PLC solutions can be easily implemented as "soft" modems using a DSP whereas this is not possible with scaled down versions of BB devices.
- *Worldwide harmonization*: the *only* available band for PLCs in the whole world is the CENELEC band as in some countries the use of frequencies above 2 MHz is prohibited in outdoor environments.
- *Coexistence*: NB-PLC networks would naturally coexist via FDM with BB-PLC networks thus segregating to two different bands the technologies supporting the very different applications of Smart Grid and home-networking.
- *Optimized design*: BB-PLC solutions like IEEE 1901 or ITU-T G.hn were not designed for Smart Grid applications but for home networking or Internet access applications only, whereas HDR NB-PLC design targets explicitly Smart Grid applications and requirements.

The above advantages are seen with great interest by the utility, automotive and appliance industries whose choices are greatly influenced by the above criteria. Among the above advantages, the ease of upgrade is of paramount importance for utilities as equipment deployed in the field needs to have long obsolescence horizons and the capability of soft upgrades without the necessity of hardware redeployment is of great economic value (note that even smart meters are considered a very long term investment). Although DSPs entail a higher cost versus spun silicon, we contend that this is sometimes outweighed by other factors. In the utility-to-meter link, the communications technology will likely not change often since the link is under the complete control of the utility so that low cost appears to be the most attractive attribute. On the other hand, for the HAN environment one would definitely favor DSP-based solutions since HAN technologies shift and change at a faster rate than what is typically under direct control of the utility. Interestingly, this connectivity uncertainty in the HAN environment may also cause a loss of interest in DSM/DR architectures involving direct load control from the utility side and thus giving a growing role to third party energy service providers (cloud-hosted energy management services).

For the above reasons, NB-PLCs exhibit very interesting advantages for appliances, meters, and PHEVs - a set of Smart Grid actors that would greatly benefit by direct connectivity with each other. If the industry converges on NB-PLC technologies for these Smart Grid applications, there would be the added advantage of being able to rely on a class of technologies that is decoupled from those BB-PLC technologies that take care of the traditional home networking and Internet access applications. Furthermore, added value services can be easily provisioned by bridging these two networks in a gateway or HEMS.

NB-PLCs also have disadvantages with respect to BB-PLC solutions when the current rush to deploy equipment in the field is taken into consideration. HDR NB-PLC solutions such as PRIME and G3-PLC have just come out and further validation in the field of these technologies and their effective range and throughput is certainly needed. Similarly, standardization efforts in ITU (G.hnem) and IEEE (1901.2) are still in their infancy. Also, NB-PLCs offer data rates of several kbps (LDR) or at most up to 500 kbps (HDR), and there is a concern that in the long term higher throughput would be required to fulfill the evolution of Smart Grid applications. These concerns seem today to perpetuate the costly paradigm of over-provisioning.

[5] An example of scaled down version of BB-PLC devices is the Smart Grid profile of the ITU-T G.hn standard. A non-SDO backed example is given by HomePlug Green PHY which is a scaled down version of HomePlug AV.

On the other hand, these concerns have not yet been supported by any quantitative analysis as an accurate estimation of what is really needed for applications close to the load is still an open problem. Thus, a clear justification on why much higher data rates may be needed is still missing - especially when considering that the largest AMR/direct load control systems in the world has been operating for the last twenty years using link speeds of only some tens of bps. Finally, any realistic estimate would also have to take into account the high correlation of the data being generated which calls for smarter sensor aggregation techniques [62], [65] (see also Sect. IV-B).

VI. Deployment Aspects: Channel Modeling and Network Topology

The PL channel is a very harsh and noisy transmission medium that is difficult to model [93]: it is frequency-selective, time-varying, and is impaired by colored background noise and impulsive noise. Additionally, the structure of the grid differs from country to country and also within a country and the same applies for indoor wiring practices. In the deployment of Smart Grid devices, and PLC sensors in particular, it is important to devise network planning tools to establish coverage. A key first ingredient is to have accurate and flexible channel modeling tools, especially statical ones. A second element is a network model based on topological properties of the PL network that serves the dual purpose of clarifying the structure of the data source (the power network itself) as well as the purpose of serving as a network planning tool.

A. Recent Advances in Channel Modeling

The issue of channel modeling is of paramount importance as any sensible communications system design must be matched to the particular characteristic of the channel. In particular, the lack of a commonly agreed upon model for the PL channel has probably slowed down transceiver optimization and the pursuit of general results [93].

Many authors have been on a quest for a better understanding of the general properties of the PL point-to-point link. Among the advances reported in the last decade, we point the most prominent ones:

- The multipath law [94].
- The classification of the several types of noise and their modeling [95], [96].
- The isotropy of the PL channel [97].
- The linear and periodically time-varying (LPTV) nature of the PL channel [98].
- The relationship between grounded and ungrounded links, which now can be analyzed under the same formalism [99].
- The log-normal distribution of channel attenuation and RMS delay spread of the channel [100].
- The recent proof that block models similar to those used in wireless and wireline DSL channels can be used in the PLC context as well - an important result since key advances in BB wireless and DSL technologies were fostered by utilizing block transmission models and precoding strategies [101].

Most of recent results are related to the BB case and were motivated by the IEEE 1901 and ITU-T G.hn projects. Now that ITU-T G.hnem and IEEE 1901.2 are targeting HDR NB-PLC technologies in the CENELEC/FCC/ARIB bands, more attention will be given to a statistical characterization of these bands and of the through-transformer characteristics. The availability of statistical channel models will aid in gaining a better understanding of the range and coverage that PLC solutions can achieve, a necessary prerequisite when deploying Smart Grid equipment in the field.

We also remark that a network scientific approach, similar to that outlined in Section VI-B, would be needed to provide a truly meaningful statistical model that can guide a large scale deployment. In the next subsections, we will review the latest results in PL channel modeling.

1) Deterministic Models: At first, PL channel modeling attempts were mostly empirical and based on measurement campaigns. The first popular model that attempted to give a phenomenological description of the physics behind signal propagation over PLs is the multipath-model introduced in [102], [103], [104], [94]. According to this model, signal propagation along PL cables is predominantly affected by multipath effects arising from the presence of several branches and impedance mismatches that cause multiple reflections. In this approach, the model parameters (delay, attenuation, number of paths, etc.) are fitted via measurements. The disadvantage of this approach is that it is not tied to the physical parameters of the channel. Furthermore, this approach is not even tied to the PLCs as it describes generic signal propagation along any TL-based channel, e.g. see [105] for the twisted pair case.

To overcome this drawback, classical two-conductor TL-theory can be used to derive analytically the multipath model parameters under the assumption that the link topology is known a priori [106]. Unfortunately, the computational complexity of this method grows with the number of discontinuities and may become very high for the in-home case (see, for example, Sect. III.A in [99]). For this reason, contributions have recently been focusing on frequency domain deterministic models based on TL-theory [107], [108], [109], [110], [111], [97], [99], [112].

TL-based channel models have today reached a good degree of sophistication as they have been extended to include the multi-conductor TL (MTL) case. Pioneering work on the application of MTL theory to power distribution networks was made by Wedepohl in 1963 [113], and tools on mode decoupling were successively introduced by Paul [114]. Building on these results, a model for including grounding in LV indoor models was proposed [111], [97], [99]. The MTL approach is a natural extension of the two-conductor modeling to include the presence of additional wires, such as the ground wire and allows to compute the transfer function of both grounded and ungrounded PL links by using transmission matrices only. These results allow us to treat with the same formalism both grounded and ungrounded indoor PL channels. As an example, let us consider a generic topology of a PL link between two devices located at nodes X and Y as shown in Figure 2. If the PL link is not grounded, then the corresponding topology is amenable of simple two-conductor TL theory description via two-port networks. If grounding is present at the main panel, a mirror topology representing what is referred to as the "companion model" must be added as a bridged tap located at the main panel as shown in Figure 2.

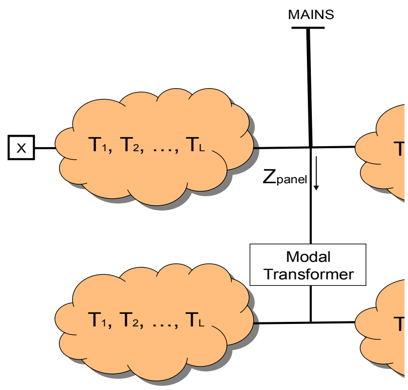

Fig. 2. The equivalent power line link in terms of cascaded two-port networks when grounding is present.

2) Statistical Models: The transfer function of a TL-based channels can be deterministically calculated once the link topology is known. However, the variability of link topologies and wiring practices give rise to a stochastic aspect of TL-based channels that has been only recently addressed in the literature. To encompass several potential scenarios and study the coverage and expected transmission rates of PLC networks, one needs to combine these MTL-based deterministic models with a set of topologies that are representative of the majority of cases found in the field. This approach is reminiscent of what has been done in xDSL context with the definition of the ANSI and CSA loops. Although this approach may be suitable for the outdoor MV/LV cases, its applicability to the in-home case may be questionable due to the wide variability of wiring and grounding practices.

An excellent approach to the generation of random in-home topologies was made by Esmailian et al. [109], where the US National Electric Code (NEC) [115] was used to set constraints on the topologies in terms of number of outlets per branch, wire gauges, inter-outlet spacing etc. This is probably the most realistic and accurate way of generating randomly channel realizations, although a generalization of this approach requires the knowledge of the electric codes of every country. Only a few other attempts have been made to develop a statistical model for the PL channel [116], [117].

A useful result for the modeling of the PL channel and the calculation of its achievable throughput was the discovery that the average channel gains $\overline{G}$ of LV/MV PL channels are log-normally distributed [100], [118], [119]. Considering signal propagation along TLs as multipath-based, channel distortion is present at the receiver due not only to the low pass behavior of the cable but also to the arrival of multiple echoes caused by successive reflections of the propagating signal generated by mismatched terminations and impedance discontinuities along the line. This is a general behavior and is independent of the link topology or, in the case of PLs, of the presence of grounding [99]. According to this model, the transfer function is [94]:

$$H(f) = \sum_{i=0}^{N_{paths}-1} g_i(f) e^{-\alpha(f) v_p \theta_i} e^{-j2\pi f \theta_i} \tag{9}$$

where $g_i(f)$ is a complex number generally frequency dependent that depends on the topology of the link, $\alpha(f)$ is the attenuation coefficient which takes into account both skin effect and dielectric loss, θ_i is the delay associated with the i-th path, v_p is velocity of propagation along the PL cable, and N_{paths} is the number of non-negligible paths. Similarly, we can write in the time domain:

$$h(t) = \sum_{i=0}^{N_{paths}-1} e_{ep}^{(i)}(t - \theta_i) \tag{10}$$

where $e_{ep}^{(i)}(t) = FT^{-1}\left[g_i(f)e^{-\alpha(f)v_p\theta_i}\right]$ is the signal propagating along the i-th path and its amplitude and shape are a function of the reflection coefficients $\rho^{(i)}$ and the transmission coefficients $\xi^{(i)} = (1 + \rho^{(i)})$ associated to all the impedance discontinuities encountered along the i-th path, and of the low-pass behavior of the channel in the absence of multipath (for analytical expressions of $\rho^{(i)}$ and $\xi^{(i)}$, see [99] for the case of forward traveling signal paths and [105] for the case of backward traveling echo paths). Thus, the path amplitudes are a function of a cascade (product) of several random propagation effects and this is a condition that leads to log-normality in the central limit since the logarithm of a product of random terms becomes the summation of many random terms. Since log-normality is preserved under power, path gains are log-normally distributed as well. Finally, since the sum of independent or correlated log-normal random variables is well approximated by another log-normal distribution [120], we can finally state that also average channel gains $\overline{G}$ are log-normally distributed.

Empirical confirmation of this property of the PL channel has been reported for indoor US sub-urban homes [100], indoor US urban MDUs [118], and for US outdoor MV underground PLs [119]. The availability of these results greatly facilitates the study of coverage which is necessary for proper planning and deployment.

B. Topological Analysis of the MV Distribution Network

A distribution network carries electricity from the transmission system and delivers it to end users. Typically, the network would include MV (less than 50 kV) PLs, electrical substations and pole-mounted transformers, LV (less than 1 kV) distribution wiring and sometimes electricity meters.

Study on the topology and electrical characteristics of the MV and LV distribution networks has two aspects of benefits: (1) providing a deep understanding of the network dynamics, hence the information traffic in the PLC network; (2) providing the topology and channel model for the PLC communication network.

1) Structure of Distribution Network: The physical layout of a distribution network is often restricted by what land is available and its geology. The logical topology can vary depending on the constraints of budget, requirements for system reliability, and the load and generation characteristics. Generally speaking, there are a few typical kinds of topology in the distribution network: ring, radial or interconnected.

A radial network is the cheapest and simplest topology for a distribution grid. This is a tree shape where power from a large supply radiates out into progressively lower voltage lines until the destination homes and businesses are reached. It is typical of long rural lines with isolated load areas. Today's grid is radially operated with respect to the current transmission system, but this topology will not hold anymore when DER will be integrated.

An interconnected network is generally found in more urban areas and will have multiple connections to other points of supply. These points of connection are normally open but allow various configurations by the operating utility by closing and opening switches. Operation of these switches may be by remote control from a control center or by a lineman. The benefit of the interconnected model is that, in the event of a fault or a required maintenance, a small area of the network can be isolated and the remainder kept on supply.

Most areas provide three phase industrial service. A ground is normally provided, connected to conductive cases and other safety equipment, to keep current away from equipment and people. Distribution voltages vary depending on customer need, equipment and availability. Within these networks there may be a mix of overhead line construction utilizing traditional utility poles and wires and, increasingly, underground construction with cables and indoor or cabinet substations. However, underground distribution is significantly more expensive than overhead construction. Distribution feeders emanating from a substation are generally controlled by a circuit breaker which will open when a fault is detected. Automatic circuit reclosers may be installed to further segregate the feeder thus minimizing the impact of faults. Long feeders experience voltage drop requiring capacitors or voltage regulators to be installed. However, if DSM is successful and peak demand per customer is reduced, then longer feeders can be tolerated and included in the design phase provided that demand peaks can still be deterministically bounded when DSM/DR applications are running - note that this may entail regulatory intervention to mandate some form of predictability in customer behavior.

2) Graph Theoretic Analysis of a Sample MV Distribution Network: We have analyzed a sample 396-node MV distribution network which comes from a real-world US distribution utility mainly located in a rural area. This is a first step in achieving a better understanding of the topological characteristics of the distribution network. The logical topology is shown in Figure 3. The power supply comes from the 115 kV-34.5 kV step-down substation. Most nodes or buses in the network are 12.47 kV, and only a small number of them are 34.5 kV or 4.8 kV.

As shown in Figure 3, an MV network usually comprises different voltage levels, separated by transformers. As mentioned in Sect. V-C1, there is not enough evidence to characterize statistically the through-transformer behavior of NB-PLC signals. Thus, in the analysis of the graph properties of the distribution network, one would have to consider two extreme cases: 1) all transformers block PLC signals; 2) all transformers allow PLC signals through. The two cases become the same if appropriate couplers are installed in order to bypass transformers and obtain system-wide connectivity.

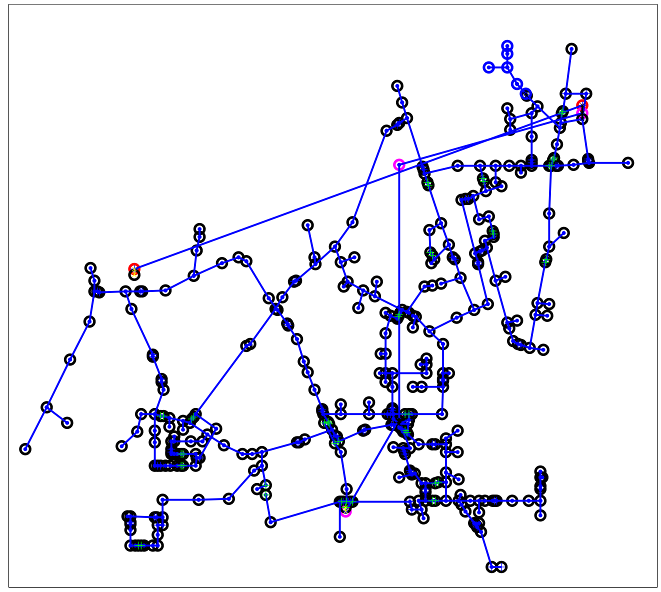

Fig. 3. A 396-node MV distribution network in a rural area of the US. Components: bus (circle), line branches (line ending with dots), switches (line ending with '+'s), transformers (lines ending with 'x's), open or out of service component (green dotted line); the node color representing its voltage levels: 115 kV (red), 34.5 kV(magenta), 12.47 kV(black), 4.80 kV(blue).

In the following topology analysis of the sample MV network, it is assumed that wireless or wired couplers have been implemented at the locations of transformers and switches, so that the network connectivity will not be affected by transformer types or switch status. On the other hand, if couplers are missing, the network will be segmented into several sections either by the transformers or by the open switches. For the sample MV network analyzed here, most buses ($> 95\%$) in the network are at the same voltage level of 12.47 kV. Therefore the topology analysis result of the separated 12.47 kV subnetwork is in fact very close to that of the whole connected graph.

The topology metrics we evaluated include the following:

- (N, m): the total number of nodes and branches, which well represents the network size.
- $\langle k \rangle$: the average node degree, which represents the average number of branches a node connects to.
- $\langle l \rangle$: the average shortest path length in hops between any pair of nodes.
- ρ: the Pearson correlation coefficient, which evaluates the correlation of node degrees in the network. This measure reflects if a node adjacent to a highly connected node has also a large node degree.
- $\lambda_2(L)$: the algebraic connectivity, which is the second smallest eigenvalue of the Laplacian matrix and is an index of how well a network is connected and how fast information data can be shared across the network.
- $C(G)$: the clustering coefficient, which assesses the ratio of nodes tending to cluster together.

In graph theory, the Laplacian matrix [121] is a matrix description of a network. For an n-node simple network without self-loops and duplicate links, its Laplacian $L := (l_{i,j})_{n\times n}$ is defined as: $l_{i,i} = deg(\text{node}_i)$; for $i \neq j$, $l_{i,j} = -1$, if node$_i$ is adjacent to node$_j$, otherwise $l_{i,j} = 0$.

The result of the analysis is listed in Table II with comparison to other two transmission networks: the IEEE-300 system represents a synthesized network from the New England power system and has a comparable network size as the 396-node MV distribution network we analyzed. The WSCC is the electrical power grid of the Western United States which contains 4941 nodes and 6594 transmission lines. It is well known that transmission and distribution topologies differ, nevertheless we decided to remark here these differences in a quantitative manner as this exercise is useful for several reasons. For example, it allows us to better understand the characteristics of the transmission and distribution networks as information sources; it allows us to optimize the design of the distribution PMU based WAMS rather than attempting to duplicate the existing transmission one which is tailored to a network with very different topological characteristics; it can tells us how the distribution topology can be "modified" to achieve some advantageous characteristics of the transmission network, i.e. shorter path lengths between nodes, better algebraic connectivity, etc.

From Table II we can see that the 396-node MV distribution network has an average node degree of $\langle k\rangle = 2.12$, which is comparable to, although a little bit lower than, that of the other two transmission networks, the IEEE-300 system and the WSCC system. That means its average connecting sparsity is about at the same level as the compared transmission networks. However, the sample MV distribution network has a much longer average path length of $\langle l\rangle = 21.10$ in hops than the IEEE-300 system and, interestingly, it is even longer than that of the much larger 4941-node WSCC system. More specifically, any node in this MV distribution network is about 16.50 hops away from node-1 or node-2 which are 115-KV buses at the HV side of the two step-down supply transformers and that may likely serve as the traffic sinks in the PLC communication network.

Looking at the algebraic connectivity $\lambda_2(L)$, the 396-node MV distribution network has a much weaker overall connectivity compared to the transmission networks, i.e. $\lambda_2(L) =$ 0.00030 versus 0.0094 (IEEE-300) and 0.00076 (WSCC). This result shows that this topology is highly prone to become a disconnected graph under node failure (islanding). Finally, the most distinctive difference we found lies in the fact that the 396-node MV distribution network has a clustering coefficient equal to zero, compared to the clustering coefficient of 0.0856 for the IEEE-300 system and 0.0801 for the WSCC system. This means that no node in the sample MV distribution network is the vertex of a complete subgraph (triangle). MV distribution networks not located in rural areas may be less prone to becoming a disconnected graph as in urban areas it is not unusual that utilities provide link redundancy, e.g. adding rings. If the distribution network becomes a disconnected graph, data connectivity obviously suffers especially if PLCs are used. This vulnerability of the distribution network can be alleviated by adding judiciously wireless links to complement the PLC based network with the goal of improving network connectivity as well as shortest path lengths characteristics. Thus, the realization of a hybrid PLC/wireless communications infrastructure that exploits synergistically the strengths of PLC and wireless could drastically improve the robustness and reliability of the data network in the distribution grid. It is then convenient to split the hybrid network so obtained into relatively independent and smaller layer 3 clusters. As suggested in [122], this can be accomplished using a two-step approach based on Graph Partitioning that yields to a robust network design characterized by balanced domains with minimal inter-domain traffic.

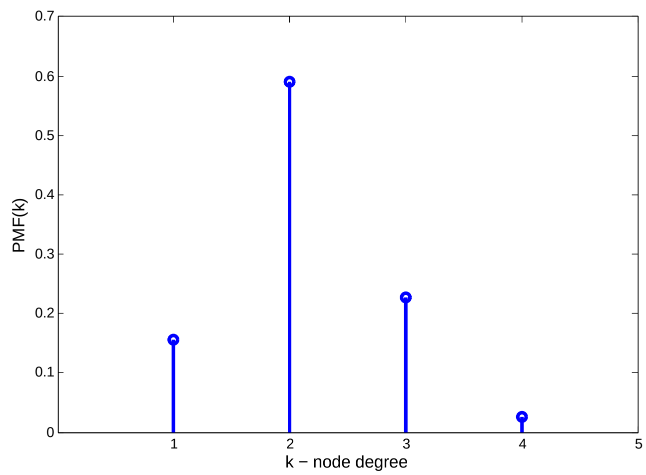

Fig. 4. The PMF of the node degrees in the sample 396-node MV distribution network.

As we have learned from [123], the average node degree of a power grid transmission network tends to be quite low and does not scale as the network size increases. The topology of a transmission network has salient *small-world* properties [68], since it features a much shorter average path length (in hops) and a much higher clustering coefficient than that of Erdös-Rényi random graphs with the same network size and sparsity. While small-world features have been recently confirmed for the HV transmission network [123], the sample MV network used here implies that a power grid distribution network has a very different kind of topology than that of a HV network and obviously it is not a *small-world* topology.

The node degree distribution of the 396-node MV distribution network is shown in Figure 4. The maximum node degree in the network equals to 4 - which is much smaller than what is found in the transmission side of the grid where maximum nodal degrees of 20 or 30 can be found. The Figure shows that about 16% of the nodes connect to only one branch, 60% connect with 2 branches, 22% with 3 branches, and only 2% with 4 branches.

Figure 5 depicts the network's spectral density, which is a normalized spectral distribution of the eigenvalues of its adjacency matrix. The spectra of an Erdös-Rényi random graph network, which has uncorrelated node degrees, converges to a semicircular distribution (see the semi-circle dotted line on

TABLE II
TOPOLOGICAL CHARACTERISTICS OF THE TRANSMISSION NETWORKS AND THE MV DISTRIBUTION NETWORK.

	(N, m)	$\langle k \rangle$	$\langle l \rangle$	ρ	$\lambda_2(L)$	$C(G)$
IEEE-300	(300, 409)	2.73	9.94	-0.2206	0.0094	0.0856
WSCC	(4941, 6594)	2.67	18.70	0.0035	0.00076	0.0801
396-node MV-Distr	(396, 420)	2.12	21.10	-0.2257	0.00030	0

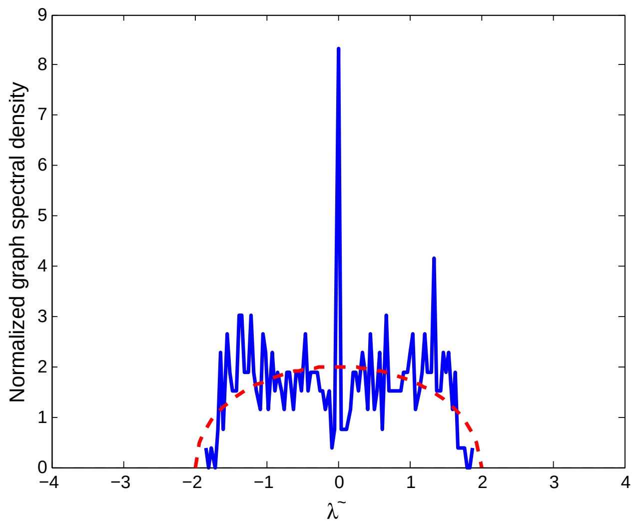

Fig. 5. The normalized graph spectral density of the sample 396-node MV distribution network, $\widetilde{\rho}(\lambda)$ vs. $\widetilde{\lambda}$: the dotted line of semi-circle represents the graph spectral density of random graph networks.

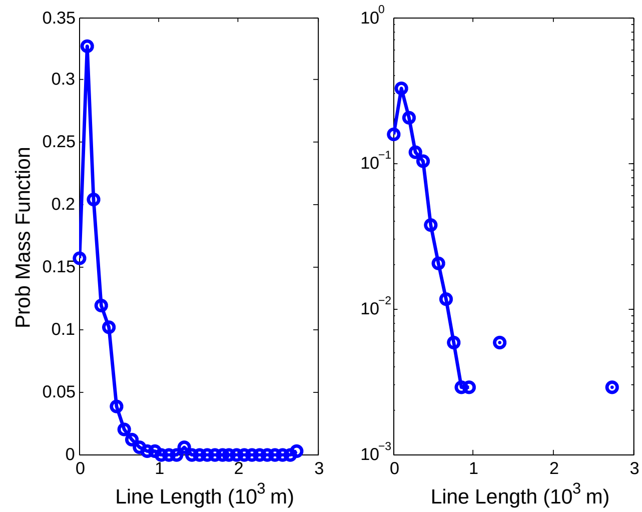

Fig. 6. The PMF of the line length in the sample 396-node MV distribution network: (left) probability versus length; (right) log-probability versus length, where the existence of an exponential trend in the tail is clearly visible.

the background in Figure 5). According to [124] the spectra of real-world networks have specific features depending on the details of the corresponding models. In particular, scale-free graphs develop a triangle-like spectral density with a power-law tail; whereas a small-world network has a complex spectral density consisting of several sharp peaks. The spectra plot in Figure 5 indicates that the sample MV distribution network is neither a scale-free network nor a small-world network.

We also analyze the branch lengths in the MV distribution network. The corresponding probability mass function is shown in Figure 6. It indicates that most of the branches are shorter than 1,067 m (3,500 ft) and the branch length distribution has an exponential tail with only a very small number of branches of extremely long length.

C. The LV Distribution Network

It is difficult to obtain example data about LV distribution network topologies. Generally speaking, an LV distribution network is radial, and has a similar network topology as an MV distribution network except that it may have more nodes with shorter branch length.

VII. RECOMMENDATIONS AND FINAL CONSIDERATIONS

We conclude this paper by making some recommendations and considerations on the methodological aspects of the pursuit for a well designed Smart Grid. Most of these recommendations transcend PLCs or any specific Smart Grid communications technology. In fact, since there are still many open problems related to the implementation of the Smart Grid, the most pressing aspect is to determine the right methodological approach rather than giving prematurely specific design recommendations on networking technologies. At the same time, we hope to leave the reader with a hint of our optimism for the use of PLCs in the Smart Grid.

A. Architecture Must Come First!

Utilities, vendors, regulators and other forces are spearheading deployments - especially in AMI. Given that what is put in the field today will be there for some decades, addressing the design aspects well from the beginning is very important. However, getting things right from the onset is complicated because of the current fog surrounding what the Smart Grid architecture should be. A fundamental priority is thus to accelerate the work on the development of an architectural framework that not only maps existing standards to the ultimate vision of what the Smart Grid will be, but also individuates standards gaps that threaten interoperability. In the US, NIST is leading an effort in this direction, trying to lay down a strategy to integrate legacy systems and new Smart Grid technologies with the goal of preserving system interoperability. An international effort aimed at defining a detailed

Smart Grid architecture to ensure system interoperability from generation to load is ongoing under the auspices of the IEEE 2030 standards project [125].

While establishing a migration path is a sensible approach, there also has to be some judicious selection of which technologies should be carried to the future, as also John Boot (GE Energy) stated in his IEEE ISPLC 2010 keynote [126]: "*There needs to be an understanding that Smart Grid Standards are forward looking only and that the migration will take perhaps decades until all equipment adheres to new standards. However, we should not try to push old standards into the future or the migration will never take place*."

B. Avoid the Temptation for a Single Networking Technology

The pressure of administrations, regulators, and some industry sectors to accelerate the deployment of the Smart Grid has sometimes pushed the collective thinking into making decisions based on two questionable assumptions:

- Off the shelf technologies, even if designed and implemented for completely different applications, can be massively and seamlessly utilized in Smart Grid - and this even before fully understanding what the actual requirements for those applications really are.
- The choice of a single technology for the implementation of certain Smart Grid applications such as DSM or AMR would accelerate reaping Smart Grid benefits since it would allow the industry to align behind a single common technology - an alignment that has not occurred yet under normal market dynamics.

The efforts devoted to the realization of the Smart Grid must take into account that the Smart Grid is, from every point of view, an *on-going experiment* - an experiment that will continue for decades to come. The understanding that the Smart Grid is still an *experiment* should lead us to make choices at this stage that encompass a diversity of solutions and implementations in order to be able to achieve a better understanding of how to cope with the very complex problem of building the Smart Grid.

Although coexistence stands in the way of interoperability, its implementation in PLC transceivers allows that diversification of deployment that is today a necessary ingredient for achieving a better understanding of how to build the Smart Grid without having to pay the penalty of interference and performance degradation. Coexistence can be seen as a form of insurance that interference will be handled, that Smart Grid communications via PLC will not suffer performance degradation, and that Smart Grid and home networking devices can be decoupled and allowed to mature at their traditional obsolescence rate - even if operating in the same band. This will allow utilities and other service providers to avoid having to resolve "service" issues caused by the interference between non-interoperable PLC devices supporting different applications.

C. Stability and Blackout Prevention: A Sisyphean Quest?

There is a very interesting body of published work that uses statistical physics tools (e.g., percolation theory in random geometric graphs [127]) to analyze "phase transitions" with application to blackout analysis [128]. The characterization of these phase transitions and their triggering mechanisms are essential to the analysis of the impact of distributed control algorithms on the overall stability of the grid. Recent analysis of US blackouts found supporting evidence of the validity of a complex dynamics behavior of the power grid [129], [130]. As stated in [131], "*The slow evolution of the power system is driven by a steady increase in electric loading, economic pressures to maximize the use of the grid, and the engineering responses to blackouts that upgrade the system. Mitigation of blackout risk should account for dynamical effects in complex self-organized critical systems. For example, some methods of suppressing small blackouts could ultimately increase the risk of large blackouts.*" Furthermore, Hines et al. also point out [132]: "*Despite efforts to mitigate blackout risk, the data available from the North American Electric Reliability Council (NERC) for 1984-2006 indicate that the frequency of large blackouts in the United States is not decreasing*."

Blackout data from several countries suggests that the frequency of large blackouts is governed by a power-law, which is consistent with the grid being a complex system designed and operated near a critical point [129]. Although it is possible that changes to the grid near the load (DSM, DR, DER, etc.) could change the power-law distribution of blackout size, not much is actually known about this. As a consequence, it is difficult today to draw general conclusions on the overall effects that "smartness" will have on the stability of the power grid [133].

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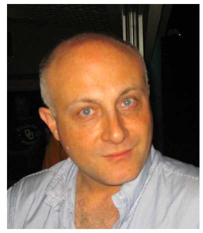

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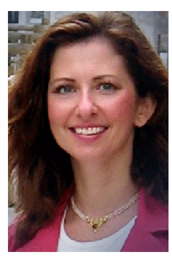

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