Power Line Communications and the Smart Grid

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***Abstract*—The design of the Smart Grid requires solving a complex problem of *combined* sensing, communications and control and, thus, the problem of choosing a networking technology cannot be addressed without also taking into consideration requirements related to sensor networking and distributed control. These requirements are today still somewhat undefined so that it is not possible yet to give quantitative guidelines on how to choose one communication technology over the other. In this paper, we make a first qualitative attempt to better understand the role that Power Line Communications (PLCs) can have in the Smart Grid. Furthermore, we here report recent results on the electrical and topological properties of the power distribution network. The topological characterization of the power grid is not only important because it allows us to model the grid as an information source, but also because the grid becomes the actual physical information delivery infrastructure when PLCs are used.**

I. Introduction

Utility companies around the world have been using PLCs for decades for remote metering and load control applications [1] using single carrier narrowband (NB) solutions operating in the kHz region at rates up to few kbps, and then upgrading to broadband (BB) systems operating in the High Frequency (HF) band (2-30 MHz) where data rates up to 200 Mbps can be achieved by commercially available products. More recently, "high data rate" NB-PLCs based on multicarrier solutions operating in the Cenelec/FCC/ARIB bands (up to ~500 kHz) have also been appearing.

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* (SG), is bringing again attention to the use of PLCs as a suitable networking technology. The debate on what is the actual role of PLCs in the SG 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 SG will exploit multiple types of communications technologies, ranging from fiber optics to wireless and to wireline (PLCs, xDSL, coax, etc.). 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 pervasive use in Europe of NB-PLCs for Advanced Metering Infrastructure (AMI). An interesting question is whether the SG efforts will have a pivotal role in fostering the success of PLCs in the market.

In the following, we will refer to the following PLC classes:

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 SDO-based BB-PLC technologies are devices conforming to the TIA-1113 (HomePlug 1.0), IEEE 1901 [2], ITU-T G.hn (G.9960/G.9961) [3] recommendations. Additional non SDO-based available technologies are HomePlug AV, HomePlug Green PHY, HD-PLC, and UPA Powermax.

Low & High Data Rate (LDR & HDR) Narrowband (NB): Technologies operating in the any of the VLF/LF/MF bands (from 3 kHz to ~500 kHz), which include the CENELEC/FCC/ARIB bands. Specifically, we have:

- *(LDR)*: Single carrier technologies capable of some 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 etc.
- *(HDR)*: multicarrier-based technologies capable of data rates ranging between some 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: IEEE 1901.2 and ITU-T G.hnem. Additional non SDO-based examples are PRIME and G3-PLC.

II. The Role of PLCs in the Smart Grid

NB and BB-PLCs provide a bi-directional communications platform capable of delivering real-time data to a variety of utility applications thus enabling utilities to identify and even predict equipment failures. Greatest suitability for PLCs is for the distribution side of the grid, which is also the part of the grid that will undergo most transformations in the transition to the SG as it will take an "active" role supporting micro-grids, distributed generation (DG), and consumer participation. Within the distribution network, there is today substantial evidence that PLCs can provide on the MV side connectivity to transformer substations in point-to-point configurations and on the LV side connectivity between transformers and meters in point-to-multipoint configurations.

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A. PLCs for MV Networks

An important requirement for future SGs 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.

An increasing proportion of MV equipment in the world have been installed several decades 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 onsite 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 [4]. Another typical application is in islanding detection. 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 [5], and it appears to be less expensive compared to other methods based on telephone cable signals. A similar approach has been investigated in [6] for the prevention of islanding in grid-connected photovoltaic (PV) systems. Other applications of PLCs can also be found in [7], [8].

B. PLCs for LV Networks

1) Advanced Metering Infrastructure (AMI): The creation of a pervasive AMI has polarized considerable attention. NB-PLCs are certainly well suited for AMI. There is a vast amount of field data about the performance of PLC-based Smart Meters as over 100 millions LDR NB-PLC devices have been deployed around the world. In many cases, NB-PLC technologies allow avoiding the capital expense of installing couplers at the MV/LV transformer since Low Frequency signals can “penetrate” the transformer - although with a substantial SNR hit. Not all NB technologies offer the same reliability in going through the transformer and often this capability depends on the transformer itself. The architectural consequence of going through the transformer is that many more smart 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. On the other hand, a BB-PLC solution would require the installation of couplers since BB signals cannot pass the transformer. 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 economical advantageous to avoid coupler installation.

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 (black-out, 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. For example, the Real-time Energy Management via Power Lines and Internet (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 [9]. 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.

2) Vehicle-to-Grid Communications: A PHEV charges 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 as the battery of the PHEV could be a resource of the SG or just of the home microgrid and 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 other wireless solution even if short range. This physical association has advantages, especially in terms of security and authentication. Although NB-PLC are impaired by several harmonics caused by the inverter and by somewhat higher attenuation, there are today several ongoing tests within the “PLC Competition” organized by the Society of Automotive Engineers (SAE) that seem to confirm that NB-PLC solutions are good candidates for PHEV applications. Since

NB-PLC are also excellent choices for meters and appliances, the availability of a single class of technologies for the internetworking of different actors in the same application is of course tempting.

3) Demand Response (DR): DR is one of the primary SG applications on the LV side and has been receiving growing interest, especially in the US [10]. 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. Due to the higher attenuation that 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), located in the home, then BB-PLC solutions are technically adequate and would provide the added benefit of being able to transfer seamlessly data from SG applications to the HAN and vice versa. Due to the lower path loss at lower frequencies, NB-PLC solutions are good candidates for DR applications for both direct and indirect load control.

4) In-Home Environment: There are intriguing possibilities of tieing SG applications with HEMS, and there is a strong belief that these application will help fostering a behavioral change in how consumer 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 made by utilities for the SG. From this point of view, segregating SG 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.

Due to availability of multiple non-interoperable PLC standards, interference between non-interoperable devices is a very important issue that has to be deal with. In fcat, when non-interoperable PLC devices share the same PL cables using the same frequencies at the same time, the generated mutual interference causes severe performance degradation or service disruption. Since PL cables are a shared medium, signals that are generated within the premises can interfere with signals generated outside the premises, e.g. at the meter, in the LV distribution part of the grid, in the neighbor's home, etc. There are today coexistence mechanisms that limit the harmful interference caused by neighboring devices and, for the BB-PLC case, the Inter-System Protocol (ISP) coexistence mechanism [11] has been ratified in ITU as Recommendation G.9972 and is also included in the IEEE 1901 Draft Standards which is close to ratification. For the case of NB-PLC, the issue of coexistence is being addressed within one of the Priority Action Plans (PAP-15) instituted by the US National Institute of Standards and Technology (NIST) [12].

C. Power Quality

Power quality (PQ) in power systems has recently become an important concern for utilities since predicting and avoiding electric disturbances guarantees the necessary compatibility between all equipment connected to the grid [13]. Within PQ monitoring and analysis, wavelet decomposition has a long tradition of applicability to the analysis of load profiles [14], electrical power supply quality [15], and protection issues [16]. One of the two PHYs of the IEEE 1901 Draft Standard is based on Wavelet-OFDM thus there is a native capability of performing wavelet transforms [17].

III. Deployment Aspects: Channel Modeling and Network Topology

The PL channel is a very harsh and noisy transmission medium that is difficult to model [18]: 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 SG devices, and PLC sensors in particular, it is important to devise network planning tools. A key first ingredient is to have accurate and flexible channel modeling tools. A second element is a network scientific model that serves the dual purpose to clarify the structure of the data source (the power network itself), as well as the purpose of serving as a network planning tool, to establish coverage.

A. Recent Advances in Channel Modeling

As one could expect, the PL channel may vary abruptly when the topology changes, i.e. when devices are plugged in or out, and switched on or off. However, even when no such event occurs, the PL channel still exhibits short-term variations due to the periodic fluctuations of the high-frequency parameters of electrical devices plugged in, which are biased by the instantaneous amplitude of the mains voltage. In addition, the noise injected into the channel by appliances is also dependent on the instantaneous amplitude of the mains voltage. Therefore, the channel and noise are cyclostationary with a period that is typically half the mains period. Notwithstanding harsh channel conditions, current BB-PLC standards (IEEE 1901, ITU-T G.hn) allow achieving up to ~200 Mbps PHY data rates when the 2-30 MHz band is used. The use of optional bands 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.

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 few years, we here point out the most prominent ones (for more details, see [19]):

- The linear and periodically time-varying (LPTV) nature of the PL channel [20].
- The relationship between grounded and ungrounded links, which now can be analyzed under the same formalism.
- The log-normal distribution of channel attenuation and RMS delay spread [21], [22].
- 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 - a very important result since key advances in BB wireless and DSL technologies were fostered by utilizing block transmission models and precoding strategies [23].

The availability of statistical channel models can aid in gaining a better understanding of the range and coverage that PLC solutions can achieve, a necessary prerequisite when deploying SG equipment in the field. We believe that a network scientific approach, similar to that outlined in Section III-B would also be needed to provide a truly meaningful statistical model that can guide a large scale deployment. At the same time, the analysis will benefit the management of the physical infrastructure itself. Recalling that the availability of accurate planning tools greatly fostered the deployment of the cellular infrastructure, we remark that the recent availability of PLC statistical results constitute the first necessary step towards the development of PLC planning tools.

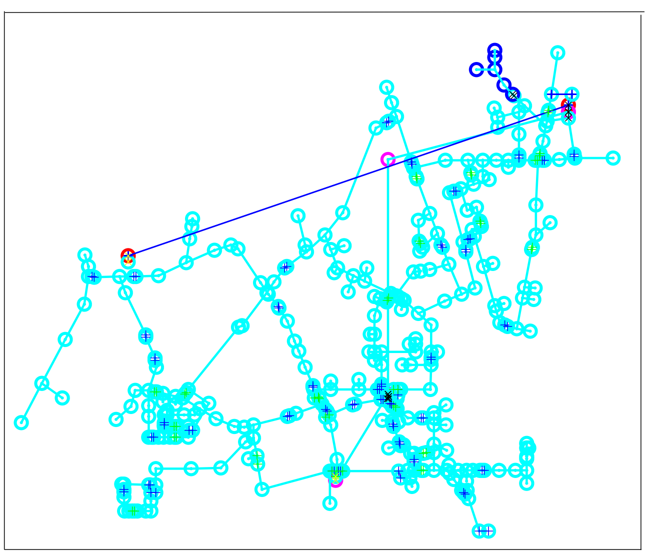

Fig. 1: A 396-node MV distribution network. Components: bus (circle), line branches (cyan line ending with '.'s), switches (blue line ending with '+'s), transformers (black lines ending with 'x's), open or out of service component (green dotted line); the node color representing its voltage levels: 115 kV (red), 34.5 kV(magenta), 12.47 kV(cyan), 4.80 kV(blue).

B. Topological Analysis of the MV Distribution Network

Study on the topology and electrical characteristics of the MV and LV distribution networks yields two important benefits [24]: (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.

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 1. 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. 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.

The result of the analysis is listed in Table I 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.

From Table I 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 high voltage 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. 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.

IV. What PLC Technology is Best Suited for 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, US regulations 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. 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 SG applications.

A compelling advantage of using PLCs is that the traditionally separated functions of sensing and communicating blur together and thus one does not have to rely on the availability of another communication channels which may be costly to install. 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. Form 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. 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.

NB-PLCs have several advantages when compared to BB-PLCs when AMI 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. 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*: devices operating in the CENELEC/FCC/ARIB bands would naturally coexist via FDM with BB HAN technologies in the HF band thus segregating to two different bands the technologies supporting two very different sets of applications.
- *Optimized design*: BB-PLC solutions like IEEE 1901 or ITU-T G.hn were not originally designed for SG applications but for home networking or Internet access applications only; on the other hand, HDR NB-PLCs solutions being developed in G.hnem and IEEE 1901.2 are explicitly targeting SG applications and requirements.

Among the above advantages, the ease of upgrade is very important to 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. 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 utility complete control. Therefore, a lowest cost and reliable alternative could appear to be a more attractive choice; on the other hand, one could also argue that soft upgrades are cheaper for achieving higher and higher reliability across years. When it comes to the HAN, one would definitely favor DSP-based solutions since it has to be taken into account that 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.

For the above reasons, NB-PLCs exhibit very interesting advantages for appliances, meters, and PHEVs - a set of SG actors that would greatly benefit by direct connectivity with each other. If the industry converges on NB-PLC technologies for these SG 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

TABLE I: 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

range and throughput is certainly needed. Similarly, standardization efforts in ITU (G.hnem) and IEEE (1901.2) have just started and 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 SG applications. These concerns, however, seem to perpetuate the costly paradigm of over-provisioning.

V. Conclusions

We have here analyzed the role that PLCs can have in the SG. Although the technology is today mature and field proven, there are two aspects that can truly hinder the success of PLC in the market. One is the commercial pressure to jump too quickly on the bandwagon of SG applications with the wrong PLC technology. A second impediment for the mass adoption of PLCs in the SG is the issue of interference caused by the multiple non-interoperable standards available today. This last problem may be solved adopting coexistence mechanisms that have the goal of limiting the harmful interference caused by non-interoperable neighboring devices. Although coexistence stands in the way of interoperability, one has also to recognize that there is no clear incumbent in the PLC world so that coexistence will practically be a form of insurance that PLC interference will be handled and that SG and Home Networking applications can be decoupled (even when operating over the same band) and allowed to mature at their traditional obsolescence rate. Thus, although the very concept of coexistence becomes moot once the industry aligns behind a common technology, PLC coexistence can be considered as a "necessary evil" that will allow current non-interoperable standards to operate in the presence of each other. Furthermore, PLC coexistence will also allow that diversification of deployment that is today a necessary ingredient for achieving a better understanding of how to build the SG.

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