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# PLC for the Smart Grid: State-of-the-Art and Challenges

## Invited Paper

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**Abstract**—This paper aims to review systems and applications for power line communications (PLC) in the context of the Smart Grid. We discuss the main applications and summarise state-of-the-art PLC systems and standards. We report efforts and challenges in channel and noise modeling, as well as in the development of transmission technology approaches.

**Keywords**— power line communication, smart grid.

## I. INTRODUCTION

The exploitation of the power grid to transmit data is the essence of power line communication (PLC) systems. PLC has been deployed by power utilities since about 1920, initially for communications over high voltage lines between remote stations. The main application was load control and, more recently, PLC has enjoyed high interest for automatic meter reading (AMR). A broader set of applications of PLC in the context of the Smart Grid will be developed in the future. This is because PLC exploits the existing power lines to convey data, allowing it to potentially reach any device connected to the power grid at reduced deployment costs [1].

In this paper, we will first describe several application scenarios of PLC for the Smart Grid in Sec. II.A, followed by a review of state-of-the-art PLC technologies in Sec. II.B. Sec. III will report efforts and challenges in channel characterization and modeling. Advanced multicarrier modulation schemes will be outlined in Sec. IV, where we will highlight the importance of using reliable transmission techniques to cope with the challenges imposed by the hostile propagation medium. Finally, conclusions will be drawn in Sec. V.

## II. PLC FOR SMART GRID COMMUNICATIONS

### A. Application Scenarios

We believe that PLC will be applied to provide two-way communication in all three Smart Grid domains, namely transmission, distribution and user domains, exploiting high voltage (HV), medium voltage (MV) and low voltage (LV) lines as shown in Fig. 1.

Power line communication can provide communications in the transmission side of the network for the delivery of several applications, for instance, for remote fault detection, remote station surveillance, or state estimation. The use of

PLC over MV lines can provide communication capabilities between sensors located in substations so that status can be monitored, and faults detected and isolated. Power line communication can also be exploited for the detection of islanding events.

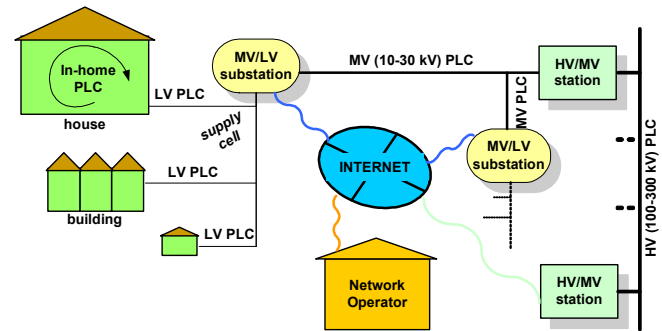


Fig. 1. PLC and application areas.

The main application in the LV part of the network is automatic meter reading and smart metering. For this application, PLC has already enjoyed a great deployment success, with about 90 million meters installed in Europe, and many more installed worldwide. Sensing, command, and control applications are also of great interest for applications inside a home or building. The in-home PLC network can be exploited for energy management purposes, together with a wide set of home automation applications for increasing security, comfort and quality of life. Finally, two further PLC application areas lie in the management and control of micro grids, for example local generation grids using renewable energy sources such as solar cells and wind turbines, and in the connection between electrical vehicles and the grid, which can offer a wide set of applications.

### B. PLC State-of-the-Art Technologies

Most PLC systems deployed in Smart Grid scenarios are based on low data rate techniques where signalling takes place over a narrow frequency band (NB) with single carrier modulation techniques, such as frequency shift keying (FSK) modulation. Recently, the need for higher data rates has triggered the development of NB PLC systems in the 3 to 500 kHz band (in particular in the CENELEC bands 3-148.5 kHz and in the ARIB and FCC bands up to 500 kHz)

using multicarrier modulation in the form of orthogonal frequency division multiplexing (OFDM) [2]. In particular, two important standardization efforts related to high rate NB PLC had been started in 2010 by the International Telecommunication Union (ITU G.hnem) and IEEE (P1901.2) for the use of frequency bands below 500 kHz for data rates up to about 500 kbps, which both were ratified at the end of 2011.

In addition to NB approaches, broadband (BB) PLC technology can cover an important role in the Smart Grid. BB-PLC has enjoyed a great success for high-speed home networking. Two standards have been recently released, namely, IEEE P1901 and ITU G.hn which operate in the 2-100 MHz and 2-250 MHz bands, respectively, and promise rates in excess of 500 Mbits/s.

Despite the existence of commercial PLC systems and recently released standards, the application of PLC in the Smart Grid poses a number of challenges due to the difficulty to establish reliable communications over a hostile medium. Therefore, Sec. III is dedicated to describing the main characteristics of the power line channel. Thereafter, in Sec. IV, we provide an overview of advanced transmission techniques that are capable of addressing the channel and noise effects.

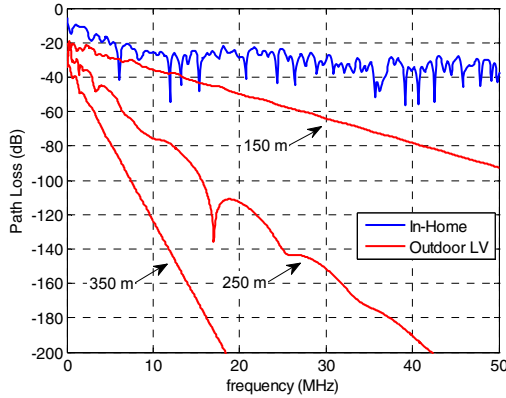


Fig. 2. Magnitude responses of a typical in-home PLC channel and of LV reference channels from the OPERA project.

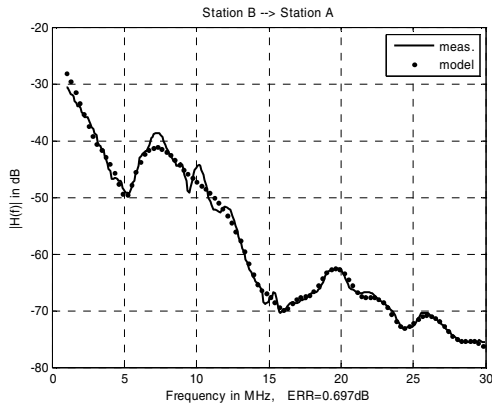


Fig. 3. Magnitude response of a measured MV channel and result from least square fitting with an error of 0.697dB.

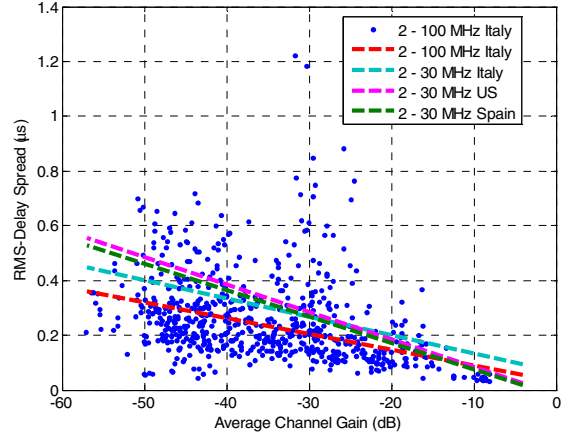


Fig. 4. RMS delay spread as a function of the average channel gain obtained during several measurement campaigns in in-home networks.

### III. PLC CHANNEL AND NOISE

#### A. Channel Gain and Frequency Selectivity

The PLC channel exhibits phenomena such as multipath propagation due to line discontinuities and unmatched loads, resulting in attenuation and frequency selective fading. Furthermore, the channel may exhibit cyclic time variations that are due to the periodic change of the loads with the mains frequency. Clearly, the channel is heavily dependent on the specific scenario and topology. The channel in HV long transmission lines is mostly affected by the attenuation due to cable length. It has been found that MV channels exhibit in general lower attenuation than LV distribution channels. This may be due to the fact that LV topologies are characterized by a higher number of branches. Outdoor LV channels have high attenuation but negligible fading, i.e., the cable attenuation dominates the propagation effects. In-home channels have high frequency selectivity and low attenuation which is due to the presence of a very high number of branches, discontinuities and unmatched loads. As an example, Fig. 2 shows a typical frequency response on an in-home channel in the band up to 50 MHz. For comparison we also show three reference channels proposed in the European OPERA project for the outdoor LV network with loops of 150, 250 and 350 m [3].

It should be noted that LV distribution networks have different structures in different countries [2]. In Europe a 230/400V 3-phase distribution system is used, which is divided into supply cells. Each supply cell is connected to a MV/LV transformer station via branches of length in the order of one km. Each supply cell collects up to 300 houses with approximately 30 houses per branch. In Asia and North America, the LV (125/250V) power supply grid uses a single or a split phase configuration. A higher density of MV/LV transformers is present with small supply cells each comprising only few houses. Branches feeding the houses are shorter and of the order of 100 m.

The characterisation of MV channels is also very important. In [4] we reported the results of measurement campaign on an MV network in China. In Fig. 3, we show a typical channel response between two MV stations. Also included is the curve obtained by fitting a multipath model to be described below, using an efficient least square approach. Some other results on the characterization of a MV network loop of length 300 m that feeds four MV/LV substations can be found in [5].

Another important aspect is the statistical characterization of the channel. Most of the results obtained so far are limited to the in-home PLC channel where several measurement campaigns, e.g., in France [6], the US [7], Spain [8], and Italy [9], have been carried out. It has been found that the in-home PLC channel exhibits frequency selective fading with attenuation that has a log-normal distribution which is the consequence of the many reflections experienced by the signal travelling along the lines. The root-mean-square delay spread (RMS-DS) also exhibits a log-normal distribution and is inversely related to the average channel attenuation as demonstrated in Fig. 4. Similar conclusions on the statistics were derived in the analysis of MV channels [5] for the network under test.

Based on experimental evidence, several endeavors have been carried out to define statistically representative channel models. A first possible approach is referred to as bottom-up approach [10]–[11]. It uses a statistical description of the network topology including cable characteristics, connections, path lengths, and loads, over which transmission line theory is applied to compute the channel transfer function. Realizations of the channel are obtained by randomly generating network topologies. This approach can be complex but provides a physical connection to propagation phenomena and topology features.

A second approach is referred to as top-down [12], which starts from a deterministic description of the channel frequency response using the multipath propagation model

$$H(f) = A \sum_{i=1}^{N_p} p_i(f) e^{-(a_0 + a_1 f^K) d_i} e^{-j2\pi f d_i / v}$$
 where the number of paths  $N_p$ , the path gains  $p_i(f)$ , the path lengths  $d_i$  are random variables, and  $A$ ,  $a_0$ ,  $a_1$ ,  $K$ , and the propagation speed  $v$  are constants obtained by fitting a set of data. Details can be found in [12].

### B. Channel Noise

In PLC the channel noise is the superposition of noise waveforms emanating from different sources. Noise is typically classified as continuous or impulsive [2]. Furthermore, narrow band disturbances originating from radio, e.g., broadcast and radio amateur signals, are also present. Continuous noise comprises of stationary background noise and time-varying cyclic noise that is synchronous with the mains cycle. Impulsive noise can be cyclic or aperiodic, as well as synchronous or asynchronous with the mains cycle. Its amplitude can be significantly higher than the background noise.

Background noise has an exponential PSD. Typically, in-home LV networks exhibit higher background noise than LV and MV networks. A typical PSD profile is reported in Fig. 5. It should also be noted that overhead MV lines are affected by background noise due to corona discharges, i.e., current pulses are generated in the conductors by the avalanche generation of free charges in the surrounding air that are induced by strong electric fields.

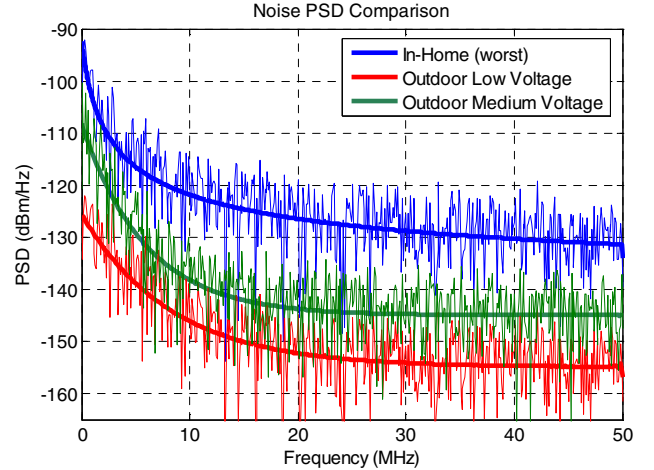


Fig. 5. Power spectral density (PSD) of background noise.

## IV. TRANSMISSION TECHNIQUES

In order to combat the hostile communication medium and provide reliable transmission performance, advanced modulation and coding techniques need to be deployed. Since the channel exhibits severe frequency selectivity, multicarrier modulation techniques are a valid solution to mitigate the inter-symbol interference effects that are introduced by such channels [2], [13]. Amongst multicarrier methods, orthogonal frequency division multiplexing (OFDM) based systems are popular due to their low complexity and pervasiveness in various communications standards. In particular, IEEE P1901, IEEE P1901.2, ITU G.hn, and ITU G.hnem define physical layers based on OFDM. OFDM is an elegant and simple solution to create ISI-free, decoupled sub-channels from a frequency selective channel provided that a cyclic prefix (CP) is added. However, the CP may reduce transmission rate, and most importantly OFDM sub-channels have a *sinc* frequency response. This translates into poor spectral confinement that makes the system vulnerable to narrow band interference, and to multiple access interference in orthogonal frequency division multiple access (OFDMA) approaches where the nodes are multiplexed by partitioning the sub-channels among the users. Further, OFDM is affected by channel time variations, which becomes more detrimental as the OFDM symbol duration - defined by the number of sub-channels - increases. In this respect, PLC channels may exhibit a periodically time-varying behavior.

We can increase OFDM performance using pulse shaping and windowing techniques as well as applying adaptive



resource allocation algorithms [14]. Another approach is to develop advanced multicarrier schemes that retain the good properties of OFDM and possibly provide enhanced performance. We refer to these schemes as filter bank modulation. Among them, filtered multitone (FMT, [13]) or filter bank based multicarrier (FBMC) methods can offer significant advantages over OFDM [15]. The main characteristic of such schemes is that their sub-channels are spectrally significantly more confined than in OFDM.

FMT is a discrete time implementation of a multicarrier system where sub-carriers are uniformly spaced and the sub-channel pulses are identical (Fig. 6). The design of the sub-channel filters and the choice of the sub-carrier spacing in an FMT system, aims at subdividing the spectrum in a number of sub-channels that do not overlap in the frequency domain, so that ICI can be suppressed and the ISI contributions lowered. In FMT the sub-channel ISI is addressed by sub-channel equalisation. FMT achieves higher spectral efficiency than OFDM since it does not require a cyclic prefix and provides SNR gains especially in highly attenuated channels [2], [13].

Filter bank schemes can support multiplexing of different users in an FDMA fashion similarly to OFDMA. FMT has superior performance compared to OFDMA because its enhanced sub-channel spectral containment allows to maintain sub-channel orthogonality when deployed in a network with unsynchronized users, that can be expected in smart grid scenarios. One important aspect is the implementation complexity, where recent progress has led to low-complexity multiuser FMT architectures based on FFT and low rate filtering [13].

Powerful extensions of the above methods can be devised by incorporating appropriate precoders and equalisers [16]. Furthermore, cross layer mechanisms, advanced management and optimisation of resources and QoS in the context of multiuser deployment can be developed. In particular, single user but also multiple user resource allocations (bits, sub-channels, codes) allow maximizing throughput [17].

Finally, an important issue is the development of physical and MAC layer solutions for coexistence and interoperability between different systems. Cognitive approaches that allow the efficient use of time and frequency resources can be followed. They may allow significant improvements compared to conventional carrier sense multiple access schemes currently adopted in PLC standards.

## V. CONCLUSIONS

We have described the use of PLC technology in the context of the Smart Grid showing that there is a broad set of applications that can benefit from it and enjoy reduced deployment costs due to the pervasiveness of the power lines. Both broadband and narrowband standards have been recently released, and field deployment is significantly increasing especially for smart metering and in-home energy management systems. It is expected that PLC technology will continue to evolve as new understanding

will be gained about smart grid application requirements, network topologies, channel and noise behaviors, and novel transmission technology and protocols will be devised.

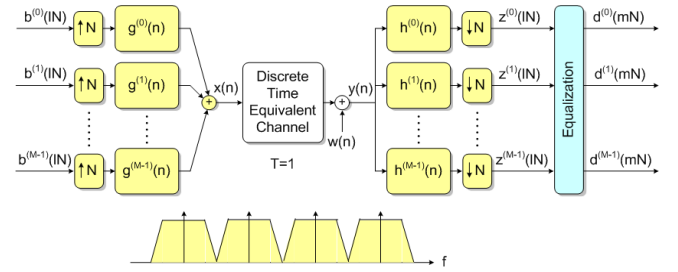


Fig. 6. Filter bank modulation scheme.

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