

# Advancing Power Line Communication: Cognitive, Cooperative, and MIMO Communication

Weiler A. Finamore, Moisés V. Ribeiro, Lutz Lampe

**Resumo**—PLC (Power Line Communication) é uma tecnologia que vem sendo ciclicamente investigada tanto para comunicação em baixas taxas quanto em altas taxas. O interesse atual em oferecer comunicação via PLC para sistemas embarcados, smart grid communications e a busca por inclusão digital é elevado. As perturbações encontradas pelos sistemas para transportar dados usando PLC requer que novos esquemas e técnicas precisam ser encontrados para introduzir uma tecnologia de nova geração para PLC. Com estes aspectos em vista, abordamos neste artigo as melhorias e benefícios que podem ser obtidos com o uso de estratégias tais como comunicação cooperativa, comunicação cognitiva e comunicação do tipo MIMO.

**Palavras-Chave**—PLC, Smart Grid. Comunicação cooperativa. Comunicação cognitiva.

**Abstract**—Power line communication is an established wired communication technology that has been investigated for low and high bit rate data communication systems. Currently, there is a great interests in providing new power line communication solutions for embedded systems, smart grid communication, and digital inclusion. Due to the impairments of electric power grids for data communications, new schemes and techniques need to be devised for the introduction of a new generation of power line communication systems. This overview-type paper addresses some of the weaknesses of current PLC technologies and the possible benefits from using concepts of cooperative, cognitive and multiple input multiple output (MIMO) communications.

**Keywords**—Power line communication, Smart grid communication, Cooperative communication, Cognitive communication.

## I. INTRODUCTION

A revival in the interest to use power line communications (PLC) systems [1]-[3] have been recently brought about by the demands posed many applications, smart grid communications [4]-[14] the most prominent. While smart grid communications are, to many countries, the main motivation behind the usage and research efforts toward PLC systems, to many emerging and underdeveloped countries the effort to lessen the digital divide is equally important. The PLC channel is generally considered to be a horrible channel, that is even worse, as advocated by some authors, than the wireless channel [5].

Despite of the channel hostility, especially recently a number of standards the use of PLC systems for data transmission in the frequency band that ranges from about 9 kHz up to about 100 MHz have been developed [2], [15],

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and soon PLC devices will be available in the market making possible transmission at data rates on the order of 1 Gbps. It should not be disregarded that, in addition, the frequency range useful for data communications can be extended up to 300 MHz.

The new PLC technology developments can benefit from the advances in signal processing and digital communications to exploit, for instance, cooperation (cooperative communication) [16]-[17], cognition (cognitive communication) [18]-[20], and diversity (multiple input multiple output, MIMO, communication) [21]-[22]. Based on these tools, a powerful and flexible generation of transceivers that will be able to address the very different demands of, for example, smart grid and multimedia communications as well as the digital divide can be developed

Only recently, the investigation of cognitive and cooperative communication for PLC systems has been addressed. The cognition concept can endow the PLC systems with the ability to transmit sharing the same bandwidth with other data communication, without harmful interference. The cooperative communication concept can, help to design PLC transceivers for transmission over long distances so as to reduce the costs associated with the inherent cost increase to include a large number of repeaters in the links. To improve PLC systems performance the use of MIMO communication, following the same trend as in wireless, exploits the existing diversity present on power lines (different differential and possible common modes) both in low and medium voltages (indoor and outdoor).

With the mentioned perspective in mind, cooperative, cognitive and MIMO issues, primarily conceived for wireless communications, will be addressed. The discussion will be directed to those aspects that require further investigation to apply cooperative, cognitive and MIMO strategies for PLC systems. Some open issues and opportunities for R&D in these very challenging fields are pointed out.

To emphasize the relevant topics related to cooperation, cognition, and MIMO communication for advancing PLC technology, this paper is organized as follows: Section II provides some background on PLC; Section III, IV and V address cognitive, cooperative and MIMO communication for PLC respectively, and Section VI poses concluding remarks.

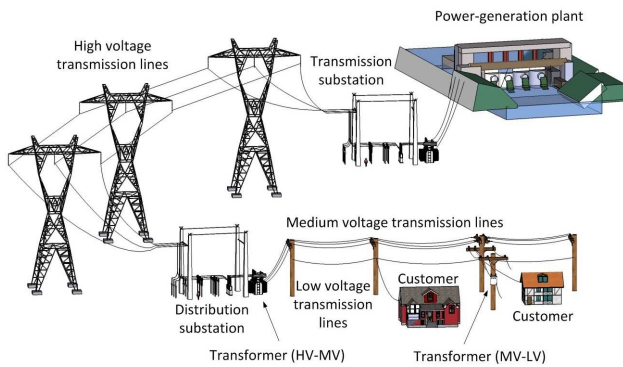


Fig. 1. The electric power grids.

## II. POWER LINE COMMUNICATION

PLC refers to the use of electric power grids as a medium for data communications considering different voltage levels (low, medium, and high voltages), frequency bandwidths (10 Hz up to 500 kHz for narrow band and 1.7 up to 300 MHz for broadband). Figure 1 depicts a sample scenario for PLC system deployments. PLC is a old idea, that has been cyclicly investigated, for dealing with new demands for data communications in scenarios that are constantly changing. In fact, at the beginning of the 20th century, it was investigated as an infrastructure for telephony and for assisting operators of distribution power grids in some USA and European cities [23]. Between 1940 and 1980, it was investigated for very low bit-rate applications, such as home automation and communication for energy transmission system [3]. From 1980 up to 2005, it was heavily investigated as a new frontier for high-speed access systems. After 2005, the PLC technology is being investigated as one of the main data communication technologies for smart grid applications, such as smart metering, and embedded system, such as vehicles, airplanes, and boat. Overall, when a PLC research cycle ends, new demands trigger a new PLC research and development cycle.

The availability of electric energy distribution infrastructures and their use for data communication in different frequency bands is the main reason for using PLC. Although power lines are not a perfect conductor for high-frequency signals suffering from impedance mismatch inside the electric power grid, having loads with time-varying behaviors (impedance and noise generation), some contributions report that PLC channel capacity can surpass 3 Gbps if the frequency bandwidth is between 0 and 300 MHz and transmitter and receiver distance is lower than 10 meters. As a result, the PLC technologies is also being investigated for providing high- and low-speed vehicular communication (cars, airplane, truck, and boat).

The electric energy distribution circuit in a vehicle is another perhaps not-so-obvious example of an application for PLC. In an automotive vehicle, sensors and actuators are connected with different protocols, namely LIN, CAN, and FlexRay [11]. PLC technology is a promising approach to reduce the wiring harness with benefits for costs, weight, and maintenance of vehicles. With the advent of electric vehicles, there is more interest in vehicular communication technology that could

also easily interface with electric power grids for billing, monitoring, etc.

The development of a new generation of PLC technologies, requires further research efforts for investigating the electric power grids as medium for data communications. In fact, the complete characterization of the PLC channels can offer valuable information for the design of new transceivers as well as PLC systems. Currently, there is a great deal of interest to characterize the power line channels in vehicles, homes, buildings, embedded systems, and electric distribution grids. Regarding in-home and in-building and high-speed data communications, the demand is for characterizing the PLC channel in the frequency band between 1.7 and 300 MHz. On the other hand, the low frequency characterization of PLC channels, which encompass the bandwidth between 10 Hz and 500 kHz, considers low-speed data communication for smart grid communication in the low-voltage (LV) and medium-voltage (MV) electric distribution grids, homes, buildings, and embedded systems.

## III. COGNITIVE POWER LINE COMMUNICATION

It is well-known that the electric power grids were not conceived for the high-frequency data communication. Also, that they are not shielded and their electromagnetic radiation may interfere with radio communication services. The advent of broadband PLC as well as the near future introduction of broadband technologies that could make use of the frequency band between 1.7 and 300 MHz for data communication, brought a great deal of attention to the potential disturbances yielded by PLC signals that could interfere with other telecommunication systems, which are operating in the same bandwidth. The rationale is that PLC technologies are not primary users in these frequency bands

According to international and national telecommunication regulatory authorities, in the 1.7-300 MHz band there are several users, such as police, army, amateur radio, AM radio stations, FM radio stations, navy, etc. However, the usage of this spectrum can be scarce in different regions, what offers a chance for opportunistic sharing of the spectrum among primary users and PLC technologies (secondary users). For doing so, new generation of PLC technologies capable of monitoring and opportunistically sharing/reusing the spectrum with primary users is of great importance, what makes spectrum sensing techniques an ultimate and timely research topic [24]-[26].

Regarding spectrum sensing, the PLC devices could make use of an antenna or a coupler connected to the electric power grid, as illustrated in Fig. 2. The use of both sensors can offer diversity and, as a result, improve the performance of detection algorithm for spectrum sensing. It is interesting to note that for frequencies lower than 10 MHz, the signal acquired from the antenna does not show the same level of disturbances as observed in the signal acquired directly from the power line with a coupler, see Fig. 3. The reason for that is the wavelength of low frequency signals, the dimensions of the antenna, the presence of nonlinear loads connected to electric power grids, and the electromagnetic wave propagation in the air and non-ideal conductor. Spectrum measurements, characteristics of

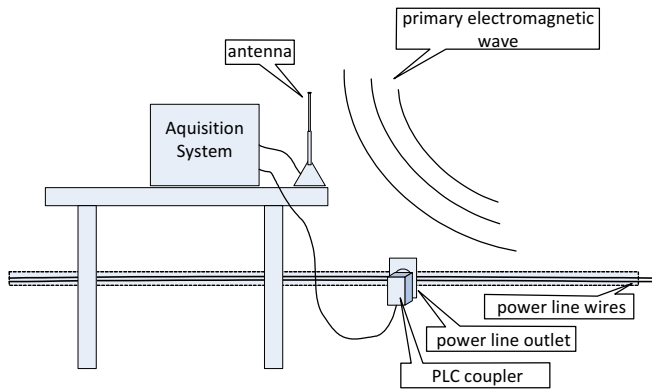


Fig. 2. The use of antenna and coupler as sensors for spectrum monitoring in a PLC system.

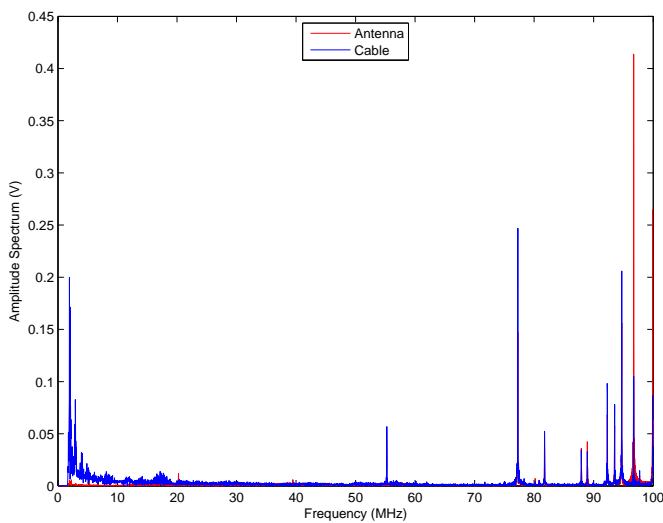


Fig. 3. A sample of spectrum measurement (1.7 MHz up to 100 MHz) using antenna and coupler in the city of Juiz de Fora, Brazil.

electric power grids, and frequency bands for PLC systems indicate that the use of distributed and cooperative spectrum sensing for improving the detection performance could be replaced by exploring the diversity in the signals acquired using the antenna and the coupler. However, it is a topic that deserves representative measurements to confirm it.

Regarding cognitive PLC systems, information about usage statistics of the frequency bandwidth between 1.7 and 300 MHz is scarce and further investigation is needed so that new PHY and MAC layers can be designed to get full benefit from cognitive concepts.

#### IV. COOPERATIVE POWER LINE COMMUNICATION

Nonlinear, time-varying and electronic based loads, regulatory constraints, impedances mismatches and increasing attenuation of signals as frequency and/or distance increase are the main reasons for performance observed in the current PLC technologies. The use of repeaters improve system performance in terms of range and possibly rate. In this scenario, the introduction of new approaches known from cooperative communications are promising for PLC systems.

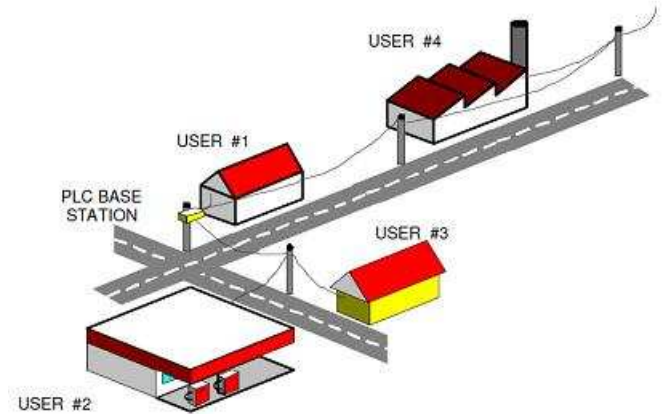


Fig. 4. Low-voltage distribution grid scenario for cooperative communication.

Figure 4 illustrates a low-voltage electric grid constituted by three users. We can assume that the PLC channel between users #2 and #4 will severely attenuate the signal transmitted because both users are far from each other. Instead of increasing transmit power, which possibly conflicts with regulatory constraints, the idea of using cooperative communication is appealing to deal with the attenuation problem. Cooperative communication for low-voltage and access system means that PLC modem in each user is capable of working as a relay to assist neighbor users.

An example of improvement that cooperative communication can offer for PLC systems is presented in Figure 5. These performance results refer to the use of single-carrier cyclic prefix (SC-CP) [27] for cooperative data communication between user #4, source node ( $O$ ), and user #2, destination node ( $D$ ). The relay node  $R_1$  is the user #1. The decode and forward (DF) as well as amplify and forward (AF) algorithms are considered [17]. In this plot,  $O \rightarrow D$  denotes the use of a SISO SC-CP scheme for data communication between nodes  $O$  and  $D$ ;  $AF O \rightarrow R_1 \rightarrow D$ , and  $DF O \rightarrow R_1 \rightarrow D$  refer to the use of DF and AF algorithms without cooperation at node  $D$ ; AF and DF refer to the use of maximal ratio combiner for cooperation at the node  $D$ . The PLC channels are linear and time invariant; and the additive noise is impulsive. The performance results reveal that a simple cooperation scheme can considerable increase the performance of PLC systems based on SC-CP scheme.

Currently, PLC systems are not cooperative. It means that there is a great opportunity for investigation and devising PHY and MAC layers that could be able to efficiently apply cooperative communication.

#### V. MIMO FOR POWER LINE COMMUNICATION

As in wireless and other wireline communication systems, the main motivation for pursuing R&D efforts toward to MIMO PLC communication is to increase maximal data rate.

Power lines in electric power grids can be constituted by three phase and neutral cables. If common and differential propagation modes are taken into account, then the number of paths between two transceivers can be twelve [28]. For

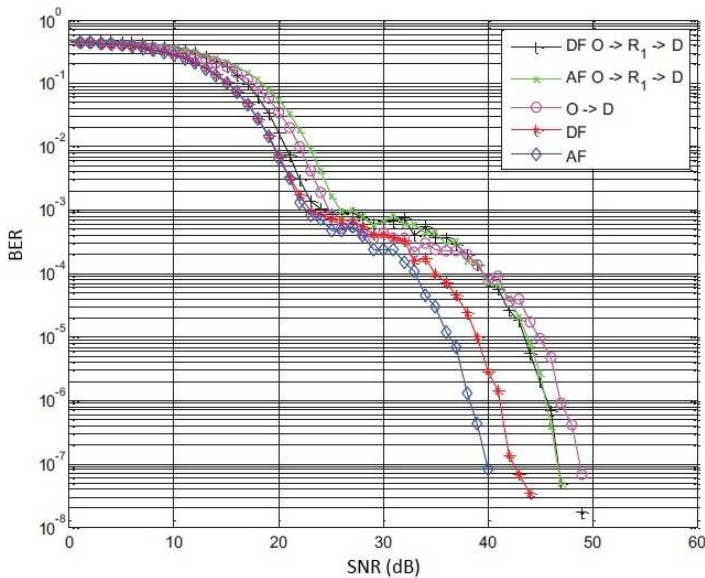


Fig. 5. Performance of AF and DF strategies for cooperative communication in a low voltage access systems when a SC-CP scheme is considered.

pursuing it, the design of coupling devices that could be able to inject and extract signals considering all paths is needed. Due to the technical difficulties to design such kind of coupler as well as the cost and viability for prototyping and manufacturing such MIMO coupler device; the research efforts are toward to  $1 \times 2$  up to  $2 \times 4$  MIMO communication schemes.

Currently, in-home MIMO PLC channels are especially investigated in Europe as MIMO PLC technologies can mitigate the weakness of wireless technologies for high-speed data communications that is to guarantee quality of service (QoS). Some results based on measurements in Europe reveal that in-home PLC MIMO channel capacity can be over 4 Gbps if the frequency bandwidth between 1.7 and 100 MHz are considered [29]. By considering spectral efficiency equal to  $\rho = 15$  bit/s/Hz, up to stable 1.5 Gbps can be achieved.

While the investigation of in-home MIMO channels is ongoing, the analysis of access electric grids, see Figure 6, for MIMO PLC communication has attracted few attention in developed countries because access systems is not one of the biggest telecommunication problems in these countries. However, for emerging and underdeveloped countries the access systems infrastructure is missing and the deployment of access systems, which were developed for developed countries, can not find payback to motivate private companies to invest in the access systems. As a result, the investigation and introduction of new and low-cost access technologies, such as MIMO PLC systems, that offer improved system performance and reliability are a very challenging and interesting research issue for countries like Brazil.

Besides the analysis of LV electric grids for MIMO PLC systems, the investigation and introduction of MIMO PLC

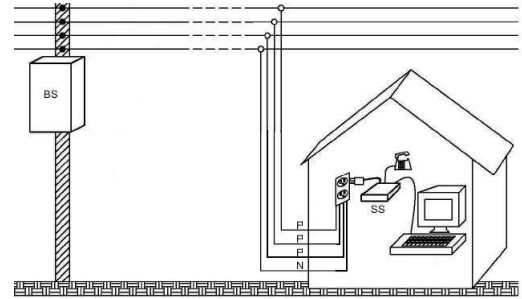


Fig. 6. A typical low-voltage electric grids for MIMO communication.

systems over MV electric grids as telecommunication infrastructure for metropolitan area network (MAN) and rural area network (RAN) are of great relevance. Usually, MV electric grids are less corrupted by the presence of man made noise and the behavior of PLC channels are more predictable. It is due to the fact that the loads connected to MV electric grids are transformer substations and MV/LV transformers, which ones may work as open circuit when frequency increases. The main drawback related to the use of MV electric grids for data communication is the higher cost of coupling devices in comparison with LV electric grids. Regarding MIMO PLC systems for MV electric grids, what are missing are measurement campaigns and channel characterization.

Overall, the introduction of MIMO communication into PLC systems can provide a new generation of PLC technologies that could be capable of offering higher throughput and guarantee of QoS in locations in which the deployment of other technologies are not financially attractive for private companies.

## VI. CONCLUSION

In this contribution we discussed PLC systems. It was highlighted that cognitive, cooperative, and MIMO communications are, as with wireless field, new paradigms for advancing PLC technologies that can enable coexistence with wireless (primary) users and overcome limitations imposed by telecommunication regulations, and offer higher performance in indoor, outdoor, and vehicular scenarios.

Although the cooperative, cognitive, and MIMO communications are very interesting for PLC systems, there are a lot of research questions to be answered that deserve attention. Standing high is the measurement and characterization, in distinct scenarios, of PLC channels in the 10 Hz to 300 MHz frequency bandwidth — gathering such information is of paramount importance to drive the development of effective, low-cost, and efficient PLC systems that make use of cognitive, cooperative and MIMO communication concepts.

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