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Review Article

Power line communication technologies for smart grid applications: A review of advances and challenges

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ABSTRACT

This paper investigates the use of Power Line Communication (PLC) for Smart Grid (SG) applications. Firstly, an overview is done to define the characteristics of PLC and PLC-based SG applications are addressed to define the compatibility of PLC. Then, the advantages and disadvantages of PLC for SG applications are analyzed to improve the issues related to PLC. Due to the past standardization problem of PLC, new protocols and standards proposed for PLC are reviewed to see possible solutions toward its standardization. In addition, both completed and ongoing developments in the PLC technologies and their worldwide implementations are reviewed in this study. Finally, open research issues and future works are given.

1. Introduction

Smart Grids (SGs) offer several advantages over traditional Electric Power Grids. The following are listed as the key advantages of SGs [1,2]:

- SGs reduce operational costs and open new markets to utility providers.
- Advanced Metering Infrastructure (AMI) enables direct communication with customer premises.
- SG networks are self-healing in case of power drops or outage.
- Infrastructures provide security against several types of attacks.
- Preserve electric power quality by increasing link quality.

Typically, a heterogeneous set of networking technologies is to be found in SGs [3,4]. One of the networking technologies proposed for SGs is Power Line Communication (PLC). PLC is the sole networking technology that has entered the market along with SG; today, it provides high speed communication to various SG applications.

Basically, PLC carries data by using a conductor and existing power lines. It provides communication services for several SG applications including Automatic Meter Reading (AMR), AMI and Home Area Networks (HAN) [5,6]. Initially, utility providers started to use PLC technology for remote meter reading. At that time, the data rate of PLC networks was very limited, up to a few kbps. Since then, and thanks to recent technology advances, the data rate of PLC networks has been continuously increasing. With the introduction of broadband PLC (BB-PLC), data rate has reached 200 Mbps. In recent years, narrowband PLC (NB-PLC) has appeared; it uses multicarrier schemes with frequencies between the 3–500 kHz [7]. Existing cabling of SG infrastructures allows for low-cost

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adaptation of PLC technology. Apart from SG applications, PLC technology is also used to provide Internet access to the end user.

The aim of this paper is to investigate the suitability of PLC for SG applications through a detailed survey of state-of-the-art technologies, related research works in progress and challenges calling for new approaches. PLC technology is investigated in Section 2. PLC-based SG applications are reviewed in Section 3 and the advantages and disadvantages of PLC in SG applications are given in Section 4. Related protocols and standards are explained in Sections 5 and 6, respectively. The performances of PLC standards and PLC protocols are analyzed in Section 7. Products based on PLC technology are reviewed in Section 8, and SG and PLC projects are reviewed in Sections 9–11. Open research issues and future work are given in Section 12. Finally, the paper is concluded in Section 13.

2. PLC technology

2.1. PLC propagation characteristics

Wireless channels exhibit different characteristics due to reflection, diffraction and scattering [8,9]. PLC channels are affected by the characteristics of wireless channels. Especially, reflections cause discontinuities in impedance [10]. Time dispersion is also present in the PLC channels, due to problems such as attenuation, delay and replication of the phase shifting occurring while signals propagate from transmitters to receivers. In order to measure time dispersion, Root Mean Squared (RMS) error is used. Time dispersion and time selectivity are the common characteristics between the PLC and the wireless channels. The PLC is inherently time selective due to the changes in impedance. On the other hand, errors occur in the wireless channels due to the noise [11]. Signal to noise ratio (SNR) determines the bit error rate (BER). BER is calculated by using the amplitude of the received signal and noise of the communication medium. Both noise characteristics and the amplitude of the received signal are therefore important in PLC channels in order to reduce BER. In addition, multipath characteristics and noise affect PLC propagation characteristics [12]. Low-voltage PLC (LV-PLC) is preferred in Europe to handle high speed communications [13]. As reflections impair high frequency signals, such signals are not used in LV-PLC.

2.1.1. Multipath propagation characteristics

Transmission behavior of PLC channels can be explained by multipath propagation approaches such as the ones proposed by Philips [14] and Zimmermann and Dostert [15]. According to the echo model, proposed in [14], the impulse response of a channel is modeled as a conflict of N Dirac pulses [16], i.e., signals coming from N different paths conflict with each other. In order to put the echo model into a function form, a complex factor ρ_i is multiplied with each of the impulses and these impulses are suspended by time τ_i each. Factors ρ_i are due to reflection. Then the channel transfer function can be described as [16]:

$$H(f) = \sum_{i=1}^{N} \rho_i \cdot \exp(-j2\pi\tau_i) \quad (1)$$

An adaptation of the echo model was proposed in [15], where an attenuation factor is added to the multipath propagation function. In this version of the echo model, each conflict of signals coming from N different paths is represented by a weighting factor g_i and a length d_i. The channel transfer function can be described as [16]:

$$H(f) = \sum_{i=1}^{N} g_i \cdot \exp((-a_0 - a_1 f^k) \cdot d_i) \cdot \exp\left(-j2\pi f \frac{d_i}{v_p}\right) \quad (2)$$

The first exponential function in Eq. (2) accounts for attenuation while the second, which contains propagation speed v_p, accounts for the echo scenario. Frequency response size gives attenuation a_0, the increment of attenuation a_1, and the attenuation exponent k. Distance d_i determines the time delay of each path. The size of the impulse gives the weighting factor g_i. N varies between the 5 and 50 [16].

2.1.2. PLC channel noise characteristics

The performance of high speed communications in PLC decreases due to frequency-dependent cable losses, multi path propagation and noise [17]. Since the additive white Gaussian noise (AWGN) assumption cannot be used to model the interference in power lines, a new model is necessary, where noise is divided into 5 classes [17]:

1. Colored background noise: It changes with frequency. The superposition of a wide range of noise sources generates colored background noise whose power spectral density (PSD) changes with time.
2. Narrowband noise: Narrowband noise consists of sinusoidal signals present at the input of broadcast stations.
3. Periodic impulsive noise asynchronous to the mains frequency: It repeats itself at 50 and at 200 kHz frequency intervals; it is caused by switched power lines.
4. Periodic impulsive noise synchronous to the mains frequency: It repeats itself at 50 and at 100 Hz frequency intervals; it is caused by power supplies.
5. Asynchronous impulsive noise: It is caused by switching transients. PSD of this noise is greater than 50 dB.

2.2. PLC communication technologies

Three different communication technologies are used in PLC, namely, narrowband transmission, spread-spectrum transmission and DSP-processed narrowband transmission. In the narrowband transmission case, a phase-locked loop (PLL) receiver is combined with the narrowband transmission technology [23]. Applicability of this approach is restricted to typical power line noise cases. In the spread-spectrum method, the bandwidth allocated for a specific signal is expanded in the frequency domain; as a result, the signal is transmitted spread over a wider bandwidth. At the receiver end, this signal is reconciled with a copy of the original waveform. Bandwidth requirements of the spread signal must be considered when the spread-spectrum method is employed. For example signaling of PLC above 150 kHz is forbidden in order to avoid interference with radio services, which use low frequency bands according to the European Union regulations [23]. In addition, PLC bandwidth is to be shared among all interested sites in the European Union. As a result of these restrictions, the narrow band spread-spectrum method is used by the consumers for efficient communication. Spectrum transmissions broader than those allowed by the European Union regulations are allowed by the US and Japanese regulations [23], where PLC can use bands up to 525 kHz for transmission. However, this frequency band may become inefficient due to interferences with aircraft navigation systems, if the PLC signaling goes higher than 180 kHz.

PLC performance is known to improve when tonal noise is present in the medium. However, when tonal noise is present, PLC spread spectrum and narrowband interfere with each other because processing gain of the power line spread spectrum is not sufficient for the tonal noise. Another disadvantage of the spread spectrum technology is that performance decreases upon defect of the PLC channel. Because of these disadvantages spread-spectrum technology is not suitable for PLC. PLC suppliers are therefore, investigating solutions other than spread-spectrum. Along this line, Sutterlin [23], introduced Digital Signal Processing (DSP) in the spread-spectrum transmission method, resulting in limited improvement. On the other hand, narrowband PLC restrictions are adequately handled by DSP. Narrowband system performance is known to decrease when impulse noise is present. According to Sutterlin [23], through the combined use of narrowband transmission and DSP, the effects of impulse noise on narrowband transmission are removed and error-free communication is achieved. The channel distortion problem of the narrowband transmission can be also addressed via DSP, thus making PLC more efficient.

2.3. Analyzing the MAC layer of PLC networks

Many users access PLC networks by using MAC protocols. MAC protocols are used by PLC to provide multiple accesses to the network, sharing of the resources and handling the traffic control functions [18]. Continuous traffic is handled by particular sharing strategies set by PLC. However, none of the sharing strategies are suitable for bursty traffic in PLC networks. Other strategies, such as the dynamic access strategy, can therefore be used for effective data transfer in PLC networks [19]. Dynamic access strategies ensure a satisfactory transmission quality for delay-critical traffic and fall into two broad categories: contention based strategies where collisions occur and arbitration based strategies that are collision free.

Time delay-critical services are not supported by contention based MAC protocols which cannot provide the Quality of Service (QoS) requirements of PLC networks, either. Token passing and polling methods are exploited by the collision free dynamic protocol [20]. Through these methods, QoS requirements can be satisfied by the collision free dynamic protocols. As the number of users increases every day, polling and token methods are becoming inefficient for the delivery of time-critical services.

MAC reservation protocols are well suited to satisfy QoS requirements [21]. Indeed, when reservation based protocols are used, users reserve a channel by the use of dynamic access methods. Variable data rates can thus be provided, depending on the type of the transmission. In this way, the network can be utilized more efficiently and QoS requirements of the users can be answered, rendering reservation-based MAC protocols suitable for PLC networks. In the following subsections, MAC protocols proposed for PLC networks are reviewed.

2.3.1. Piggybacking ALOHA protocol

It was proposed to combine the ALOHA and the piggybacking methods in order to develop a collision-free MAC protocol for PLC [20]. In this approach, through the prevention of transmission of additional request packets, traffic in the PLC channel decreases and the reliability of the channel increases. It has been shown that the Piggybacking ALOHA protocol provides efficient network utilization when the packet length is small in addition to providing the reliability needed. When the network load is low, access delay decreases if the piggybacking ALOHA protocol is used. However, when the network load is high, access delay increases whether the piggybacking ALOHA protocol is used or not. The same behavior is valid for data throughput. If small packets are sent, data throughput increases. However, if packet size is greater than 1500 bytes, ALOHA protocol achieves the same performance, whether piggybacking is used or not.

In conclusion, the piggybacking ALOHA protocol is efficient for PLC systems with small-sized packets. In this case, it is seen to increase network utilization and data throughput while decreasing the access delay time.

2.3.2. Hybrid access protocol with polling and ALOHA

The Hybrid Polling – ALOHA Access Protocol has been designed by Hrasnica et al. [20]. In this approach, a random component is introduced to produce a hybrid access method where random and dedicated components compose the signaling channel. In its channel model, when a request in a random slot is made by a station and is accepted, the station sends the packets. However, if the request is not accepted in the random slot, then a dedicated slot is used by the station to send the packets. In PLC networks with small-sized packets, network utilization decreases whether the hybrid access protocol is used or not. If the network load is high, the utilization of the network decreases due to the collisions in the channel. In that case, dedicated slots are used when a collision happens. Therefore, the hybrid access protocol is better than the ALOHA protocols for PLC systems with small-sized packets thanks to a better network utilization. On the other hand, the hybrid access protocol is not efficient when small packets are sent in highly loaded PLC networks, due to collisions resulting in an increased access delay in such networks. However, if the network load is low, access delay decreases with the packet size. On the large-sized packets case, polling and hybrid access methods have the same data throughput in PLC networks.

2.3.3. Carrier Sense Multiple Access/Collision Avoidance MAC protocol (CSMA/CA)

CSMA/CA MAC protocol is the most frequently used by access networks as it is more suitable for broadband access. Although dynamic and multi-hop topologies can be handled by the CSMA/CA MAC protocol, it cannot guarantee bandwidth and minimum latency requirements and does not support video and real time applications [22]. Although the CSMA/CA MAC protocol can be employed in PLC systems, where dynamic and multi-hop topologies are present, it is not a good choice when real time communication is needed. On the other hand, Time Division Multiple Access (TDMA) technology is a good choice as it allows for bandwidth allocation and handles multi-hop topologies, although it is not efficient for broadband communication. For this reason, IEEE 1901 has conducted research on TDMA over CSMA [22].

2.3.4. TDMA over CSMA MAC protocol

The TDMA over CSMA MAC protocol divides time into time regions [22]. Time intervals of the CSMA are determined by each CSMA region assigned to a group of stations following a competition among them. When a station wins a CSMA time region, a continuous time slot in the TDMA region is given to the station. The TDMA over CSMA MAC protocol prevents interference by avoiding the entrance of the stations to the stay-out region. In this way, neighboring stations do not interfere with each other. TDMA service allows meeting the requirements of a specific application by scheduling the TDMA channels between the stations. In this way, prioritization also can be achieved.

2.3.5. Dynamic polling of TDMA

Dynamic polling of TDMA is one of the centralized TDMA methods where, due to the variable channel conditions, the scheduling of slots is dynamically adjusted by using a scheduling table [22]. This method is used in AMR systems because it is efficient in avoiding collisions. Slots are allocated through signaling and beacons are sent by the stations to allocate a time slot. This type of allocation is known as 'semi-persistent' meaning that slot allocation lasts for one or two seconds [22]. Voice and video applications use semi-persistent allocation.

2.4. Comparison of PLC with fixed-line and wireless access technologies

Broadband services are provided by various communication technologies depending on the requirements of the application. There are two types of broadband technologies: Fixed-line technologies [22,24]:

- Hybrid Fiber Coax
- Digital Subscriber Line
- Home/Curb Fiber
- Power Line Communications (PLC)

and Wireless Access technologies [22,25]:

- Microwave links
- Multichannel Multipoint Distribution Service (MMDS)
- Local Multipoint Distribution Service (LMDS)
- Free Space Optics (FSO)
- Wireless Fidelity (WiFi)
- Satellite communication
- Cellular Networks (3G and 4G)

In general, power line communication (PLC) systems operate by applying a modulated carrier signal on the existing electrical wiring system and use the 1–30 MHz spectrum. PLC uses symmetric links and provides a data rate of up to 200 Mbps. Its maximum communication distance varies. It is 3 km in medium voltage and 200 m in low voltage. The main drawback of PLC up to now is the lack of standardization. PLC is one of the most suitable access technologies for broadband communication. Although fiber access technologies provide secure, reliable and high speed communication, they are rather expensive. As listed in Tables 1 and 2, PLC offers considerable advantages when compared with either fixed-line or wireless access technologies. The following are the main PLC comparative merits, as tabulated in Table 3:

- Ubiquity: PLC provides ubiquitous solutions. The use of existing electric power lines makes PLC superior over other fixed-line access technologies and enables remote connection. Therefore, it is one of the most suitable communication technologies for many applications requiring remote connection such as the AMR.
- Cost: PLC provides low cost communication as compared to other access technologies because it exploits existing infrastructures.
- Impact of the Environment: The deployment of PLC does not have an impact on the environment. No antennas and no additional cabling are required for its deployment, as opposed the other access technologies.
- Developing technology: PLC is a blooming technology. Although there is no global PLC standard yet, it is secure and reliable and meets QoS requirements.

3. PLC-based smart grid applications

Several SG applications use PLC; the major ones are reviewed in the following paragraphs.

3.1. Automatic Meter Reading (AMR) and Advanced Metering Infrastructure (AMI)

Two-ways communication provided by PLC enables customer devices and systems to communicate with each other in AMI. In this way, real-time pricing can be provided by offering utility providers the possibility to interact with metering devices. It also enables customers to learn their current billings. Smart metering is efficient for the utilities due to its low operational costs.

Commercial PLC products, based on Ultra Narrowband (UNB) and Narrowband (NB) technologies, are already available, while Ultra Narrowband PLC (UNB-PLC) technology is being used for remote meter reading. Even though the data throughput of UNB-PLC devices is low, their communication range is 150 km. Narrowband PLC (NB-PLC) technology is also used for certain SG applications.

Table 1
Comparison of PLC with fixed access technologies.

Access technology	Cost	Deployment	Data rate	Topology	Terminal	Communication range
HFC	Low cost where cable TV exists	Easy where cable TV exists	Varies with country	Multiple point	Constant	40 km
xDSL	Low cost	Easy	From 1.5 Mbps to 12 Mbps	P2P Point to point	Constant	From 300 m to 6 km
FTTH	Expensive	Difficult	1–10 Gbps	Multiple point and P2P	Constant	5.4 km
PLC	Easy because of exploitation of the existing wires	Easy	200 Mbps	Multiple point	Constant	3 km in medium voltage. 200 m in low voltage

Table 2
Comparison of PLC with wireless access technologies.

Access technology	Cost	Deployment	Data rate	Topology	Terminal	Communication range
Satellite	Expensive	Simple	155 Mbps	Multiple point	Constant	From 1000 km to 36000 km
Microwave	Expensive	Difficult	155 Mbps	Multiple point	Constant	5 km
LMDS	Expensive	Difficult	155 Mbps	Multiple point	Fixed	4 km
MMDS	Expensive	Difficult	10 Mbps	Multiple point	Constant	100 km
FSO	Expensive	Difficult	2.5 Gbps	Multiple point	Constant	4 km
WiFi	Low cost	Simple	11, or 54 Mbps depending on the standard	Multiple point	Mobile	100 m
3G and 4G	Expensive	Easy	1–10 Mbps	Multiple point	Mobile	Limited to mobile coverage area
PLC	Low cost	Easy	200 Mbps	Multiple point	Constant	Varies according to low or high voltage

Table 3
Comparison of PLC with other access technologies.

PLC technology	Other access technologies
Provides ubiquitous solutions	No ubiquity
Low cost	High cost
Less impact on the environment	Higher impact on the environment (installation of antennas, etc.)
Developing Technology No Global Standards	Global Standards already existing
More scalable	Less scalable
More interoperable	Less interoperable

Moreover, projects such as the High Data Rate Narrowband PLC (HDRNB-PLC) are being conducted by IEEE 1901.2 and ITU-T G.HNEM to provide higher data rates than the UNB-PLC. PLC data concentrators located at medium voltage (MV) and low voltage (LV) transformer stations function as gateways for communication between the Meter Data Collection system (MDC) and smart metering devices. A PLC data concentrator gathers and stores meter data, events and communication statistics [26]. AMR through PLC calculates the consumption of electricity based on the different time zones such as holidays or work days. It also enables detection of power theft and data collection from the other meter-reading devices, such as water meters or gas meters. Also, two-ways communication provided by PLC allows for gas or water supply cut off on demand, when a customer will not need them for a long time.

3.2. Electric vehicle-to-grid communication over the PLC

The battery of a Plug-in Hybrid Electric Vehicle (PHEV) is charged by an Electric Vehicle Supply Equipment (EVSE). Communication between the PHEV and the Utility is currently a field of intensive research, because peak load can be controlled if communication is made possible. PLC can provide secure communication of PHEV with the EVSE. Different PLC technologies such as BB-PLC and NB-PLC have been tested by the Society of Automotive Engineers (SAE). NB-PLC has given better results in terms of applicability [26].

3.3. Demand Side Management (DSM)

Demand Response (DR) answers the demands of different energy requests. DR controls power conditions and increases the efficiency of the system by using a real time pricing scheme. In addition, peak demands can be reduced by DR and customers can monitor their energy consumption through PLC between the Utility and household appliances. The implementation of a DR system is based on BB-PLC and indirect control, through a gateway. One of these indirect load applications is Home/Building Energy Management System (HEMS/BEMS). Instead of BB-PLC, a cheaper solution, such as the NB-PLC, can be used for DR system [26].

3.4. In-home environment

The BB-PLC, the core of the HEMS, is not a solution for all the needs because of the wide spectrum of requirements the SG is expected to satisfy and the accordingly big variety of the technologies employed to these ends. A solution to this problem is the restriction by CENELEC of the communication of the SG applications within a single band in order to separate them from any other system. The HEMS offers benefits to the Utility such as reliability and reduction of the peak demand thanks to the continuous reporting of energy demands to the Utility.

Nowadays, Hybrid AC/Direct Current schemes are being investigated. DC is advantageous for the in-home environments, both for the generation and storage of energy. In addition, NB-PLC and BB-PLC technologies operate better over DC lines because they provide noise-free lines for communication [26].

3.5. Remote fault detection

PLC uses High Voltage (HV) lines to remotely detect faults such as insulators out of order, short-circuited insulators or cable outbursts [26]. Remote fault detection offers prevention of traffic losses and avoidance of signaling errors in the network. When a fault is detected in the network, PLC sends an alert message notifying the user that reliability of the links is low; data transmission over broken links is thus prevented.

3.6. Voice and data transmission over PLC

Higher data rates can be attained by PLC technology over HV lines [26]. The United States Department of Energy (DOE), American Electric Power and Amperion are carrying out research to this end. Multicarrier modulation (MCM) based modems can be used [27], to reduce both the bit error rate (BER) and the power spectral density through multicarrier spread spectrum (MC-SS) technology (see Table 4).

4. The advantages and disadvantages of PLC in smart grid applications

At its present state, PLC technology offers several advantages for SG applications due to its distinct properties such as high speed communication and low voltage power lines; at the same time, it faces considerable challenges. The PLC advantages list includes [28]:

- Wide Coverage: Existing power lines can be used to extend PLC coverage required by SG applications.
- Low Cost: Existing wires are used by PLC technology; no additional cabling is required. PLC is a cost-effective solution to monitor the usage and outage of the power remotely.
- Flexibility and Range: PLC networks are flexible; they provide long range communication.
- Mobility: Wide coverage communication can be realized by using PLC. In this way, PLC provides mobility for SG applications.
- Ease of Installation: The installation of PLC networks is easy for indoor implementations. For this reason, it is also suitable for low-cost systems.
- Stability: PLC provides a stable communication system for SG applications. On the other hand, the following are drawbacks for the use of PLC in SG applications [28].
- High noise sources over power lines: Noise is injected in power lines by many sources such as electric motors, power supplies and radio signal interferences. Therefore, BERs are typically high in PLC networks.
- Capacity: A recently developed communication modem for PLC networks has 45 Mbps data rate but cannot work with full capacity because of the shared environment of the power lines. Due to its shared medium, PLC technology is not well-suited for SG applications.
- Problem of open circuit: Communication over power lines is lost with devices on the side of an open circuit.
- Lack of Interoperability: PLC has interoperability problems with various types of devices.
- Attenuation and Distortion of Signal: Physical topology of the network and fluctuation of the load attenuate and distort the signal in power lines.
- Security: Twisted and protected cables are not used for power lines. For this reason, Electro Magnetic Interference (EMI) produced by power lines can be received by radio receivers and may result in a security problem.
- Inadequacy of the regulations for broadband PLC: New regulations such as limits on the transmitted energy limit and on the frequency bands must be set to prevent interference and enable broadband PLC (see Table 5).

Table 5
Advantages and disadvantages of PLC for SG applications (summarized).

Advantages	Disadvantages
Wide Coverage	High noise sources over power lines
Cost	Capacity
Flexibility and Range	Problem of open circuits
Mobility	Attenuation and distortion of the signal
Easy Installation	Inadequacy of the regulations for broadband PLC
Stability	Lack of interoperability

Table 4
A summary of PLC-based SG applications.

Applications	Purposes
AMR and AMI PLC	Offers real time pricing
Vehicle to Grid Communications over the PLC Smart Grid Applications	Provides cost-efficient communication between car and EVSE
Demand Side Management (DSM) PLC Applications	Checks power consumption and provides energy efficiency
In-home Environment Smart Grid PLC Applications	Supplies reliability and mitigates peak demand
Remote Fault Detection	Remote diagnoses of faults on the cables, out of order insulators, etc.
Voice and Data Transmission with PLC	Provides higher data rates with the Broadband PLC for voice and data communication

5. Power line communication protocols

Several PLC protocols are in use today. They differ in channel access modulation, frequency and channel access procedure.

5.1. X10 protocol

X10 is the oldest PLC protocol and uses Amplitude Shift Keying (ASK) modulation. Products based on the X10 protocol are generally unidirectional, with a few exemptions of bidirectionality. Bandwidth utilization and reliability of the protocol are poor in noisy environments. The bandwidth is about 60 bps over a 60 Hz power line.

5.2. CEBus protocol

The CEBus standard uses spread spectrum modulation on power lines. Spread spectrum involves starting modulation at a certain frequency and modifying the frequency during its cycle. CEBus data rate is almost 10 kbps and it can be used for homes and offices for light-duty applications. Collisions are avoided by Carrier Sense Multiple Access (CSMA) and Collision Resolution and Collision Detection (CRCD).

5.3. LonWorks protocol

It is a peer-to-peer communication protocol developed by Echolon Corporation. Collisions are avoided by using CSMA. The modulation scheme is narrowband spread-spectrum. It prevents errors in the presence of noise. It is used in North America and Europe because of its narrowband nature. It is mostly used for control and automation applications, such as lighting and Heating, Ventilating and Air Conditioning (HVAC).

5.4. HomePlug 1.0 protocol

Existing electrical wiring is used by HomePlug 1.0 protocol. The protocol handles subchannels by dividing the available bandwidth. Its data rate varies from 1 to 14 Mbps and nodes can adapt to the optimal data rate automatically. Collisions are avoided by using the CSMA/CD scheme. For QoS provisions, the HomePlug 1.0 protocol defines four priority levels [29].

5.5. Simple Control Protocol (SCP)

SCP has been created by Microsoft Corporation to provide secure and robust peer-to-peer communication between small and low-cost devices. It is suitable for low-speed PLC networks and for several application types such as sensor networks, energy monitoring systems and AMR.

5.6. Living Network Control Protocol (LNCP)

Networking cost in the home environment is low when using LNCP. It uses peer-to-peer communication and it is a multi-master system. A single bus is used by the protocol. For this reason, the bus can be placed anywhere. LNCP allows for the remote control of home devices. Its design is based on an 8-bit processing microcomputer and as few as just 17 bytes of volatile memory and nonvolatile memory [31].

Table 6
PLC protocol-based systems.

Protocol	Used by
X10 Protocol	Home Automation System
CE Bus Protocol [26]	Home and Building Automation System
LonWorks Protocol [26]	Home Environment
Home Plug 1.0 Protocol [29]	Home Environment, IPTV, gaming
Simple Control Protocol (SCP) [30]	Home Automation System
Living Networks Control Protocol (LNCP) [31]	Home Networking, Digital TV
Home Network Control Protocol (HNCP) [32]	Home Control Network System

5.7. Home Network Control Protocol (HNCP)

HNCP is a four-layered protocol used for monitoring home devices: vendors and home devices provide interoperability by using a standard message set. HNCP defines the interface to the devices modems and encapsulates each of its layers for reliability. It also uses categories in its address system. Standard message system consists of message code, input increments and return increments. Master nodes can control other devices by using interfaces specified by HNCP [32] (see Table 6).

6. Power line communication standards

Major existing standards for PLC are the IEEE P.1901 and 1901 (broadband power line standards), the ITU-T G.9960 standard, the CENELEC EN 50065 standard, the ETSI standard, the HomePlug AV standard, the HomePlug AV 2 Standard, the High Definition Power Line Communications (HD-PLC) standard and the Universal Power Association standard. These are briefly reviewed in the following paragraphs.

6.1. HomePlug AV standard

HomePlug AV standard has been produced by HomePlug Powerline Alliance to improve the HomePlug 1.0. HomePlug AV's purpose is the distribution of audio and video content throughout the house. In contrast, HomePlug 1.0's purpose has been the distribution of broadband internet access throughout the home [33].

HDTV and VOIP applications are supported by HomePlug AV, which has 200 Mbps data rate at the physical layer and 80 Mbps data rate at the MAC layer. HomePlug AV corrects the errors by using turbo convolution codes and ARQ. Maximum bandwidth is achieved by the HomePlug AV for audio and video applications. Moreover, HomePlug AV provides security as it uses 128 bit AES encryption.

6.2. HomePlug AV 2 standard

HomePlug AV 2 is produced by HomePlug Powerline Alliance. Faster data transmission is handled by HomePlug AV 2 standard by using the IEEE 1901 standard. Application layer performance increases when the HomePlug AV 2 standard is used because more than one video streams are visualized simultaneously with HomePlug AV 2 and more nodes are used as repeaters to handle more extended signal all over the house [34].

6.3. High Definition-Power Line Communication (HD-PLC) standard

HD-PLC has been designed by Panasonic and it uses OFDM. Digital information is sent via power lines when the HD-PLC is used. Existing circuits such as electrical cables can be used to construct HD-PLC networks. For high frequencies, HD-PLC uses Wavelet OFDM modulation. Its maximum data rate is 210 Mbps. HD-PLC estimates new channels through channel estimation methods, thus increasing the data rate for each carrier. Data rate increases according to channel's SNR. Noise causes fluctuations of the signal; channel estimation methods estimate the channel characteristics as a function of the channel noise, resulting in an increased data rate. HD-PLC is compatible with traditional home appliances. It offers security by using AES 128 bit $*$ 2 and it can measure the transmission rate – a functionality through which the communication status can be easily known [35].

6.4. IEEE P.1901 standard

The Medium Access Control (MAC) and the Physical layer are covered by IEEE P.1901 standard. There are many P.1901 standard applications such as data, audio and video distribution over home networks, smart grids or plugged-in electrical vehicles. The IEEE P1901 standard employs frequencies lower than 100 MHz; these frequencies are used by the PLC devices. IEEE P.1901supporting devices provide connection from first mile to last mile for broadband services. Additionally, these devices may be used on Local Area Networks (LANs) [36].

6.5. ITU-T G.9960 standard

ITU-T G.9960 is an International Telecommunication Union (ITU) standard designed to handle the high speed networks necessary for HDTV. ITU-T G.9960 includes specifications on the physical layer. It transmits multimedia content over the power, coaxial, phone or other wiring. Throughput attained is 20 times higher than that of existing wireless systems and 3 times higher than that of existing wired systems. Chip manufacturers use this standard for the production of transceivers that can work with DVD players, TV sets, home audio systems, etc., [37].

6.6. CENELEC EN 50065 standard

CELENEC EN 50065 is the European Union standard for PLC. It uses the frequency band between 9 and 140 kHz. Upper bound is increased to 500 kHz in Japan and USA, thus increasing throughput up to 1000 bps. Applications such as electrical network load management or remote metering thus fall into the scope of PLC [20].

6.7. ETSI standards

ETSI develops standards to provide interoperability between devices produced by different manufacturers described as follows.

- Reference Network Architecture Model: PLC network architecture is specified by this document. PLC external interfaces are identified in document [38].
- Coexistence of Access and In-House Power Line Systems: Frequencies, which are same, cannot be used for preventing the interference while accessing the PLC and when PLC accessed to medium. For this reason, this ETSI standard tries to give different frequencies to access and in-house [39].
- PLT LCL Review & Statistical Analysis: Some conditions such as Variations of Earthing and Country, differences of Operator, topologies of phasing and distribution, housing types, which can be domestic or industrial, are thought for measuring loading of the local network by this ETSI standard [40].
- Hidden Node Review and Statistical Analysis: Transverse Transfer Loss distribution is measured by this standard. It is measured according to the frequency of carrier. Carrier frequency depends on the sockets' location, phase conditions of sockets [40].

6.8. Universal Power Line Association (UPA) standards

Some specifications are made by the Universal Power Line Association. These specifications cover different expectations of the PLC technologies. There are three areas, which are thought by the UPA, and three specifications for the PLC. One of the areas is Coexistence. UPA makes a specification in 2005 for the coexistence. Second of them is accessing the Broadband over Power line (BPL) networks. UPA makes a specification for accessing in 2006. Third specification is done for in-home systems and solutions in 2006.

6.9. IEEE 1901 broadband power lines standard

IEEE 1901 standard is developed for making high speed communication which is over 100 Mbps. Frequencies of the devices, which use this standard, are lower than 100 MHz and HAN and access applications can be done by using these devices. Two broadband PLC technologies, which are FFT-OFDM and Wavelet-OFDM, are identified by this standard. FFT-OFDM and Wavelet-OFDM are some of the ETSI standards for PLC that focus on the PHY/MAC layers. Devices compatible with Wavelet-OFDM and FFT-OFDM are also compatible with the Home Plug AV and HD-PLC standards [26].

7. Analysis of the physical layer of PLC

As mentioned earlier, the main advantage of the PLC is that it uses the already installed physical network. However, the physical network places some obstacles or limitations to the communication. This is why devices such as repeaters or bridges are needed when the distance exceeds certain limits [41]. To overcome such limitations, PLC employs different protocols, each featuring different physical performance characteristics. Performance of the major PLC protocols and standards is analyzed from the physical layer aspect in the following paragraphs (see Table 7).

7.1. The physical layer of the X-10 PLC protocol

X-10 is the earliest PLC protocol [41]. It uses the Amplitude Shift Keying (ASK) Modulation scheme to transmit information from sender to receiver over electric power lines [41]. Variations in the information transmission method employed may be found across the various existing X-10 products; unidirectional versus bidirectional communication is such an example. X-10 avoids noise interference in the channel by using an 120 kHz AM carrier and a 0.5 watts signal. A high frequency signal is used for data encoding. Reliable communication is secured by sending each bit twice; data rate is therefore limited to 60 bps. A three-cycles gap is introduced between every two successive packets. Two 11-bits messages are used by each packet resulting in a 0.8 s latency. As a consequence, reliability cannot be satisfied in noisy environments and this affects the usability of the X-10 protocol.

7.2. The physical layer of CEBus PLC protocol

CEBus provides reliable peer-to-peer communication by employing the Carrier Sense Multiple Access/Collision Detection and Collision Resolution (CSMA/CDCR) scheme [41]. This MAC protocol offers reliability by sensing the channel. If the channel is empty, node transmits a packet otherwise node waits until the channel becomes idle. In this way, CSMA/CDCR protocol avoids collisions by removing interference between transmitting nodes.

Intellon Corporation of Ocala, FL, USA provides a technology for the power line physical layer of the CEBus. Intellon's spread-spectrum technology provides spreading of the frequency band, unlike other spread-spectrum techniques that employ frequency hopping and direct sequence spreading. CEBus data throughput is 10 kbps; receiver and sender addresses are included in all the packets. A table of 360 digitized values forms the waveform for the CEBus spread spectrum. Frequency bands used are 200 kHz, then 400 kHz, then 100 kHz and then 200 kHz. This causes a 100 s latency of communication; yet, it helps avoid interference with higher layers.

7.3. The physical layer of LonWorks PLC protocol

LonWorks is a peer-to-peer communication protocol developed by CELENEC that uses Carrier Sense Multiple Access (CSMA) to control channel access. Narrowband spread-spectrum is used to avoid interference caused by the noise. Signal deterioration is lower in narrowband spread-spectrum than in wideband spread-spectrum. LonWorks uses DSP to prevent interference and provide communication over varying distances. In contrast to LonWorks, used worldwide thanks to its narrowband basis, CEBus is only used in limited applications. The PLT-21 transceiver is the most popular device for use with the LonWorks protocol; it implements the CELENEC access protocol. The CENELEC access protocol operation is switched on and off by the user, thus eliminating the need for complex control algorithms.

7.4. The physical layer of HomePlug 1.0 standard

HomePlug 1.0 Standard uses the Orthogonal Frequency Division (OFDM) technique, also used by DSL, IEEE 802.11a and IEEE 802.11g [42]. The frequency band between 4.5 MHz and 1 GHz are used by the 84 subcarriers employed in OFDM. Differential modulation techniques render equalization unnecessary. Reliability is offered through the use of Forward Error Correction (FEC) and interleaving, thus avoiding noise interference. Disrupted carriers are removed by the Tone Allocation modulation in HomePlug 1.0 standard, Error rates thus decrease and channel adaptation becomes easy. In conclusion, FEC and Tone Allocation modulation increase throughput.

7.5. The physical layer of HomePlug AV standard

Many applications use HomePlug AV thanks to the higher throughput it provides [42]. Major physical features

Table 7
An overview of PLC standards and their purposes.

PLC Standards	Purpose
HomePlug AV Standard [33]	Distribution of audio content through the house
HomePlug AV 2 Standard [34]	Fast data transmission
HD-PLC [35]	Handling of higher data rates
IEEE P.1901 Standard [36]	Home Environment, IPTV, gaming
ITU-T G.9960 Standard [37]	Distribution of audio, video and data over the home network, over smart grids and to plugged in electric vehicles
CELENEC EN 50065 Standard [20]	Handling high speed networks for HDTV
ETSI Standards [38–40]	Preventing noise interference
UPA Standards [26]	Avoiding interference; increasing communication speed
IEEE 1901 Broadband Power Lines Standard [26]	Providing high speed communication

of the HomePlug AV standard are summarized as follows. 1. Noise caused interference is prevented by the Turbo codes. 2. Several modulation types such as BPSK, QPSK, and 8 – QAM are supported. 3. Synchronization is possible between the HomePlug AV devices and HomePlug 1.0 devices; interoperability is thus achieved. 4. Different modes such as session setup, multicast and broadcast are included. Mode is chosen according to network conditions. 5. Different modulation types are used. Channel quality is estimated via the SNR; if noise exceeds a set threshold, a different channel is chosen for reliable communication.

8. PLC products

Various PLC products made available by different manufacturers are reviewed in the following paragraphs [43–45].

8.1. Power line smart transceivers

Echolon produces PLC Smart Transceivers to achieve robust and low cost communication. These transceivers can be used in different kinds of applications such as home, building, industrial, and automation applications. Different types of Smart Transceivers produced by Echolon, are listed below.

- PL 3170 Power Line Smart Transceivers: Functions of Interoperable Self Installation (ISI) is added to Power Line Smart Transceivers in this product of Echolon. PL 3170 offers a 4 KB application space to the users and users can detect devices automatically via ISI.
- PL 3120 and PL 3150 Power Line Transceivers: These products combine low price, high performance and big size. They are suitable for many environments such as home, building, and industrial.

8.2. PLM-1 modem ASSP for PLC

The PLM-1 modem, produced by NEC for PLC, implements half duplex transmitter and receiver. Narrowband frequency shift keying (FSK), advanced processing techniques are used by this modem for increased performance. It offers increased communication speed and provides flexibility as to the carrier frequencies. The same medium may be shared by this modem and other PLC technologies because it employs protocol neutral technology. In this way; more than one protocol can share the same power line. Forward Error Correction mechanism is used for error detection and correction for reliable communication.

8.3. Cisco-Linksys PLK300 Power Line AV ethernet adapter kit

A single port and a four part Power Line AV Adapter are used by the Linksys Power Line AV Adapter. This product allows for the use of existing electrical outlets to create an in-home network over existing cabling. The adapter uses the HomePlug AV standard, which connects any computer on a wired Ethernet LAN without any installation process. New devices are easily added by plugging the Power Line AV Adapter in an electrical outlet.

8.4. Sling Media SlingLink Turbo Powerline Kit (SL200-100)

Network connectivity is provided by SlingLink Turbo when it is connected to any electrical wall outlet. It provides fast data rates in the order of 85 Mbps. It has four switched ports which serve to connect Slingbox with game console, DVT, computer or any other devices. High speed internet access is also provided by SlingLink Turbo Powerline Kit over existing power lines, while the product remains interoperable with any other home router.

8.5. Panasonic high definition power line communication ethernet adaptor

Panasonic HD-PLC product can connect to any AC outlet at home. It can be easily set up without the need of a computer and provides fast, reliable and secure communication It attains a 210 Mbps data rate, includes error correction mechanisms and AES 128-bit encryption.

8.6. ZyXEL PLA400 200 Mbps powerline HomePlug AV desktop fast ethernet adapter

ZyXEL creates an in-home network over existing power lines using its PLA-400 v2 product that increases the data rate up to 200 Mbps. Network resources can be shared and high speed communication is supported.

8.7. Corinex communications HD200 powerline network adapter

This Corinex power line networking product connects a gaming console to the fast Internet.

8.8. IOGear powerline stereo audio system

IOGear Powerline Stereo Audio System consists of three modules, the Powerline Stereo Audio Station, Powerline Stereo Audio Adapter and the remote control. It can be used for applications which need remote control, such as the Smart Grid applications.

8.9. NETGEAR XAV2001 Powerline AV 200 adapter

High speed internet connection is provided by NETGERAR's Powerline AV 200 Adapter. It is used especially for connecting HDTVs, Blu-ray players, DVRs, PCs and game consoles to the internet. Power is automatically shut down when it is not used for a long time, thanks to the NETGEAR Green Features [45].

8.10. Cisco-Linksys PLUSB10 Instant PowerLine USB Adapter

This product is used in homes and offices to connect computers to the network. When the USB adapter connects to a PC, the PC connects automatically to the powerline network. Its data rate is 12 Mbps. Sharing of files, printers and gaming devices is provided.

8.11. Monster PowerNet 100 expansion module

Ethernet connection is extended by this product. Expansion module can be plugged into any wall outlet to provide Ethernet connection over large spaces. Performance and speed increases when PowerNet 100 Expansion Module is used.

9. University projects related to PLC

PLC related research projects carried out by universities are presented in the next paragraphs.

9.1. Open PLC European Research Alliance (OPERA) project

The objective of this project is to develop the PLC into an alternative broadband technology that will provide secure communication to the customers. PLC technology development is based on deploying certain units common in different environments.

- Digital division reduces by deploying PLC in rural areas.
- PLC is deployed in multiple dwelling units using fiber cables into the buildings, in order to provide high speed communication.
- Low-cost double play services are offered by deploying PLC in high density areas through the interconnection of multiple dwelling units (see Table 8).

This project was supported by many Universities such as Swiss Federal Institute of Technology, the University of Comillas, the University of Dresden, and the University of Duisburg-Essen, as well as by many PC manufacturers such as EDEV-CPL, ONI, PPC, by utilities such as IBERDROLA, LinzAG Strom, and UNION FENOSA, by technology providers, developers and manufactures. The OPERA project was completed in 2007 and it produced many new results for PLC, including new equipment, new prototypes, development of the PLC technology, new services for PLC, standardization [46].

Table 8
PLC products and their manufacturers.

Product (s)	Manufactured by
Power Line smart Transceivers [43]	Echolon
PLM-1 Modem ASSP for PLC [44]	NEC
Linksys PLK300 Power Line AV Ethernet Adapter Kit [45]	Cisco
SlingLink Turbo Power Line Kit [45]	Sling Media
High Definition PLC Ethernet Adapter [45]	Panasonic
PLA400 200 Mbps Power Line HomePlug AV Desktop Fast Ethernet Adapter [45]	ZyXEL
HD200 Power Line Network Adapter [45]	Corinex
Power Line Stereo Audio System [45]	IOGear
XAV2001 Power Line AV 200 Adapter [45]	NETGEAR
Linksys PLUSB10 Instant Power Line USB Adapter [45]	Cisco
PowerNet 100 Expansion Module [45]	Monster

9.2. Development of EMI suppression techniques for PLC systems project – Nanyang Technological University

Nanyang Technological University is carrying out a PLC project whose objective is to study and lower PLC network emission. Its partners include Network Research Technology Center (NTRC) and Agilent Technologies, Singapore who contribute the $ 240,000 budget for this project. According to the results of this project, PLC can be used as an alternative technology for high speed communication. Indoors tests for PLC are performed, showing that PLC systems emissions are 20 dB higher than the FCC Part 15 49.5 dB V/m limit [47]. Power transformer and isolation transformer increase the radiated emissions. If the power transformer is removed, radiated emission decreases. Research is currently being carried out on the reduction of the radiated emissions by the Electromagnetic Effect Research Lab (EMERL).

9.3. PLC project – Anna University – K.B. Chandrasekhar Research Centre (Chennai, India)

This project consists of the following two parts.

- Part 1: The Low Tension (LT) Power Line Segment Downstream of the Distribution Transformer is studied in this part. Distribution Transformers provide communication up to a few hundred meters by using mostly underground cables. This project aims to measure the LT segments for communication at high frequencies and for increasing the data rate up to 1–2 Mbps. Spread-spectrum design is also a part of this project in order to achieve communication over the LT segment.
- Part 2: The High Tension (HT) Power Line Feeder Segment Feeder line sets out from the Substation and is fed by the Distribution Transformers (DT) all the way through underground cables. It provides short range communication in urban environments. The feeder can have a different numbers of DTs. This project aims to measure the HT segment in order to increase the data rate. Different technologies are used for multiplexing at the physical layer, such as Spread Spectrum and Orthogonal Frequency Division Multiplexing (OFDM), in order to investigate the potential of PLC segments for Internet services provision. According to these project findings, PLC segments are suitable for Automatic Meter Reading (AMR), Distribution Automation (DA), Low Data Rate Networking, etc., [48].

9.4. Ultra wideband PLC above 30 MHz project – Queen Mary, University of London, UK

The goal of this project is to investigate and analyze the transmission and noise properties of a broadband power line channel. Broadband channel response is defined by using the time domain channel. Project results verify that a communication link with frequency between 50 and 550 MHz is provided by the indoors power line channel. Channel capacity increases greatly at the 500 MHz bandwidth area, while data rates at the Gbps range can be obtained for channel frequencies between 50 and 550 MHz at indoors environments [49].

9.5. Device control via PLC project – University of Guelph

The goal of this project is to design and implement robust PLC and to design a system for remote control of the devices powered from the outlet. A household computer is employed to monitor the power outlet over the power lines. The computer receives commands issued remotely on the powering of the system. Design is based on three components, namely, power switching devices, PLC and the user interface [50].

- Power Switching Device: It switches the device on and off. Current state of the device can also be monitored. It functions in three different modes: enable, override and manual off.
- Power Line Communication: PC and power line modem communicate with each other using an RS232/TTL converter. FSK is used for sending and receiving data by the power line modem. The data rate is 600 bps. But the communication medium has bad quality characteristics because of the power line.
- User Interface: User interface is designed and programmed in PHP. Monitoring and control can be done remotely or locally. A command line system server is used for realizing user actions. User is informed about the system status through visual and textual responses. This project shows that PLC is suitable for many applications such as energy conservation, thermal regulation, and building monitoring.

9.6. Modeling the colored background noise PLC channel based on artificial neural network project – Tianjin University

PLC is known to be inappropriate for high frequency signal transmission. This project investigates the characteristics of the PLC, especially those related to high frequency signal transmission and noise. Project aims include noise classification in PLC channel, background noise color identification and mathematical modeling of the noise [51]. Artificial neural networks are used for the study of colored background noise. Results on PLC channel' background noise modeling are satisfactory and are verified by simulations based on real power line channel noise characteristics.

9.7. Design of medium voltage PLC spread spectrum carrier modulation system based on embedded system project – Changsha University of Science and Technology

Known PLC shortcomings, such as the fast decay of the signal or the fluctuation of the signal over the power lines f are investigated in this project. Findings resulted in the design of the PL2000A Power Line Modem. PLC problems are here addressed by embedded system design and a spread-spectrum scheme. A major finding of the project is that distribution network automatic system applications can use MV spread spectrum communication to obtain a low cost, feasible communication system as it has been verified by field tests [52].

10. European union projects related to PLC

A considerable number of European Union (EU) projects, either in progress or concluded, are focused on PLC.

10.1. On-going EU projects

10.1.1. Distribution line carrier: Verification, integration and test of PLC technologies and IP communication for utilities, EU project (DCL + VIT4IP)

DCL + VIT4IP project (2010–2012) is focused on the fact that there do no exist medium or low voltage distribution networks in Europe. PLC technology could provide advanced distribution networks; yet, state-of-the-art PLC technologies do not offer reliability, quality of service or interoperability for distribution network applications. The project aims to design and test a high speed, narrowband PLC over Internet Protocol (IP). For this purpose, the DLC + VIT4IP project implements five different solutions for integrating and extending current PLC technologies. IP version 6 is implemented first; followed by automatic measurement, configuration and management. The security structure of the PLC is implemented as a third stage while provision of real time capabilities is the fourth stage. The last stage is channel modeling and network planning through simulation tools as well as field tests on these channel models. A prototype for high performance communications infrastructure is the project outcome [53]. Partners include organizations from Italy, Deutschland, Israel, Belgium and the United Kingdom (see Table 9).

10.1.2. Modeling of electromagnetic transients and PLC energy services EU project

This EU project (2010–2012) is coordinated by the French Universite Blaise Pascal Clermont-Ferrand II. It focuses on broadband data transfer over power lines using PLC; standardization for broadband communication using PLC technology is not yet available, however. A major PLC problem is that of Electromagnetic Compatibility (EMC). EM transients of lightning and switching surges cause failures and defects in the PLC channel. Further study is necessary to fully understand the power line behavior as to energy storing and distribution when the Transmission Line (TL) is in transient mode. EM transients are hard to prevent. The project aims to provide protection against EM transient by reducing the complexity of EM transients in the electric power system [53]. Furthermore, Impulsive noise and EMC issues are dealt with in [54].

10.1.3. Real-Time Energy Management via Power-Lines and Internet EU Project – REMPLI

The REMPLI EU project (2003–2014) aims at remote reading out of energy metering devices over the Internet and the power lines and in this way collecting data on energy consumption. It provides energy management and automated energy billing to help users control energy consumption. Broadband PLC is implemented for the remote reading of meters. REMPLI project is comprised of four (4) to be addressed: broadband PLC solutions for multi-entity systems, hardware and software design to implement the

Table 9
An overview of PLC projects conducted by universities.

Project title	Objectives	Conducted by
OPERA [46]	PLC as an alternative for broadband communication; secure communication through the PLC	University of Comillas, University of Dresden, etc.
Development of EMI Suppression Techniques for PLC Systems [47]	Handling lower emission	Nanyang Technological University
PLC Project [48]	PLC at higher frequencies and with increased data rate	Anna University K.B. Chandrasekhar Research Centre (Chennai, India)
Ultra Wideband PLC above 30 MHz Project [49]	Monitoring and analyzing the transmission and noise properties of a broadband power line channel	Queen Mary, University of London, UK
Device Control via Powerline Communication Project [50]	Design of secure PLC and remote control systems	University of Guelph
Modeling the Colored Background Noise of PLC based on Artificial Neural Network Project [51]	Investigating and testing the characteristics of PLC	Tianjin University
Design of Medium Voltage Power Line Spread Spectrum Carrier Modulation System Based on Embedded System Project [52]	Solutions to the PLC problems through embedded system and spread spectrum schemes	Changsha University of Science and Technology

REMPLI project, identification of the major characteristics of the system and field tests of the designed system to verify the results [53].

10.1.4. OMEGA – The home gigabit access EU project

The OMEGA project develops user friendly home access networks with high transmission speed, around Gbps; this is of interest to many applications that require high bandwidth, such as 3D gaming, and high definition radio. Among the solutions offered by the OMEGA project is the provision of advanced home network standards and the contributions to the standardization of home networks. New business opportunities are opened for manufacturers and network operators. Among the numerous partners of this project are Orange Labs and France Telecom, since France is the coordinator of this project, as well as the University of Rome, INSA-IETR, IHP Microelectronics, Lantiq, Thyvia, etc., [55].

10.1.5. PoweRline Intelligent Metering Evolution (PRIME) EU project

This project is developed by IBERDROLA's Networks business area. Its main purpose is the development of international standards for interoperability of the different devices and systems which are produced by different manufacturers [56].

10.2. Completed EU projects

10.2.1. Open PLC European Research Alliance (OPERA) for new generation PLC EU Project-Phase 1

Opera Phase 1 (2004–2006) focused on PLC for data transmission using the existing electric network, to keep the costs low through the exploitation of already existing infrastructure and cabling. The main purpose of Opera Phase 1 was to provide PLC to all European cities as a low cost broadband access solution. Opera Phase 1 offered improved performance in transmission speed low cost products, a unique international regulation, and interoperability between the existing systems and newly designed systems [53].

10.2.2. Open PLC European research alliance for new generation PLC integrated network, Opera Phase 2

Opera Phase 2 project (2007–2008) was aimed at making the PLC a viable alternative technology for broadband access in all European cities. This target would be achieved through standardization, improvement of the technology, offering of intelligent grid and telecom services – all developed within the Opera Phase 2 project. Partners included universities from Spain and Germany and industries from Spain, Slovenia, United Kingdom, Brazil, etc. Competition in the PLC area has increased as a result of this project and new services have been added to the PLC technology, such as smart home, video streaming, and Voice over IP (VoIP) [53].

10.2.3. IPv6, QoS & POWER line integration EU project (6POWER)

The 6POWER project (2002–2003) purpose was to develop broadband access over the Power Lines with IPv6 in Europe. This was sought through six (6) different work packages: coordination, interconnection and dissemination for the application field; combination of IPv6 services with the PLC; network architecture design and implementation; definition of the PLC devices; specifications for the next generation of applications and evaluation of the system. Specific protocols have been designed to support IPv6 and QoS through Power Line and interoperability has been provided among the different devices over IPv6. Different applications such as voice over IP, music server, and video streaming have been adapted to operate with IPv6 over the Power Line network [53].

10.2.4. Development of a cost efficient innovative reusable integrated power supply system, enabling interference free high-speed PLC architecture for the affordable smart house EU Project – FLEXOLINE@HOME

The main purpose of this project (2006–2009) was to achieve 10 times higher data rates while decreasing the interference caused by the EM in PLC. FLEXOLINE@HOME provided these features while decreasing the installation time and cost. Robust and safe power supply and high speed communication have been provided and the combined introduction of a power supply and a communication system to every European home has improved the quality of life in the EU. A product of FLEXONLINE@HOME with direct impact on the environment was the reduction of electromagnetic smog. FLEXONLINE@HOME's project coordinator was the Innowazja Polska Spolka Z Organizona Odpowiedzialnoscia industry, supported by many other industrial partners from Poland, United Kingdom, Romania, France, Spain, etc., [53].

11. PLC-based smart grid pilot projects and field tests

11.1. Development of PLC protocol by Atos Origin and Trialog – Published by ERDF

ERDF, largest European electricity distribution network operator published specifications on the PLC in October 20, 2009. Atos Origin and Trialog developed these specifications to implement communication with metering devices or concentrators. ERDF's Linky Smart Meter project and PLC Laboratory have developed this pilot project [57] (see Table 10).

11.2. Puerto Rico Electric Power Authority (PREPA) – Smart Grid Broadband – over – PLC Pilot Project

The Broadband over Power Line (BPL) communications pilot project is carried out by the Puerto Rico Electric Power Authority (PREPA), in cooperation with the Alabama BPL technology provider IBEC (International Broadband Electric Communications). This pilot project aims to deploy smart meters to remotely turn power on and off, while implementing the smart grid in the PREPA service. Smart meters were first deployed in 2010; since then, their use has been spreading daily thanks to this pilot project [58].

11.3. West east electricity transfer pilot project and field tests

The People's Republic of China government has constructed three transmission lines known as the West–East Electricity Transfer Pilot Project (2010) System capacity has been planned to increase and electricity shortages be wiped out upon completion of this project. The objective of this project is to construct the highest voltage, longest transmission lines in the world. China solves the increasing demand for electricity using smart grids along with the constructed transmission lines. Field tests show that, upon completion of this project, China would meet the 15% of the energy demands through renewable energy sources (RES) and would reduce the dependency on carbon in 2020 [59].

11.4. E.ON smart grid with broadband PLC pilot project

IP Communications architecture is provided for the E.ON smart grid pilot project by Power Plus Communications AG (PPC), a BPL provider for smart grids, and CISCO. The E.ON pilot project aimed at simplifying the available Cisco solutions on the Smart Grid. Field tests for this project carried out using the BPL technology and IP based data transfer rates between 5 and 30 Mbps, verify that PPC's medium voltage technology is a suitable extension to the CISCO available solution (Cisco's Connected Grid). Project uses the Cisco Smart Grid Router and switches; according to the tests, these are compatible with the BPL networks. Thus there is no need for fiber optic cables and this reduces the cost of the system. Tests show that fast and efficient smart grids can be handled with a the combination of Westfalen Weser, PPC and Cisco technologies, resulting in increased reliability in the power grid and decreased costs for the installation of the system [60].

11.5. High-speed narrowband PLC in smart grid landscape pilot project

The purpose of this project was to implement a low cost, high speed narrowband PLC platform which can provide long-range communication for the Smart Grid [62].

Table 11
SG projects and preferred communication technologies.

Project type	DSL	PLC	GPRS
Small projects	1	4	4
Medium projects	3	7	2
Large projects	1	2	0
Total	5	13	6

Table 10
A summary of European union-supported PLC projects.

Project title	Purpose
DCL + VIT4IP [53]	Designing and testing of the high speed, narrowband PLC over IP
Modeling of Electromagnetic Transients and PLC Energy Services EU Project [40]	Handling secure communication against the EM transient
Real-time Energy Management via Power Lines and Internet EU Project [40]	Remote reading of energy metering devices using power lines and the Internet
OMEGA [55]	Providing high speed home access networks
PRIME [56]	Enhancing international standards for PLC
OPERA [53]	Phase 1- Developing low cost broadband access Phase 2 Making the PLC a viable alternative technology for broadband access in all European cities
6POWER [53]	Providing broadband access over the Power Lines with IPv6 in Europe
Development of a cost efficient innovative reusable integrated power supply system, enabling interference-free, high speed PLC architecture for the affordable smart house EU project [53]	Increasing data rates and decreasing interference

Table 12
Pilot projects on the PLC-based SG applications.

PLC-based smart grid pilot projects	Goal	Promoter
Development of PLC Protocol by Atos Origin and Trialog [35]	Developing some specifications for PLC	ERDF and PLC Laboratory
Smart Grid Broadband over Power Lines Communications Pilot Project [61]	Deploying the smart meters to PREPA service	PREPA and IBEC
West East Electricity Transfer Pilot Project [59]	Increasing the system capacity, and preventing the electricity shortages	China government
E.ON Smart Grid with Broadband PLT Pilot Project [60]	Reducing the system cost with simplifying the Smart Grid solutions of Cisco	PPC AG and Cisco
High-Speed Narrowband PLC in Smart Grid Landscape Pilot Project [62]	Designing narrow band high speed PLC platform for Smart Grid	KEMA Consulting GmbH, Lancester University, Austrian Academy of Sciences, KEMA Consulting Europe, The Israel Electric Corporation
DSL, PLC, and GPRS for Smart Grid Pilot Project [61]	Investigating different communication solutions in smart metering	KEMA Consulting GmbH
Lianxiangyuan Pilot Project [13]	Providing interactive communication between the customers and power grid by using PLC	State Grid Corporation of China
The pilot project in Yard 95, Fucheng Road [13]	Constructing smart intelligent platform between the users and the power grid	State Grid Corporation of China

11.6. DSL, PLC, and GPRS for smart grid pilot project

Carried out in Germany, this project investigates different communication solutions in smart metering. DSL, PLC, and GPRS are examined; according to experiments, PLC is the choice for the smart metering because it offers solutions to power utilities with PLC infrastructure. Table 11 shows the technologies used in different sizes of the projects. As it can be seen in Table 11, PLC is preferred by the pilot Smart Grid projects because it provides low cost and reliable communications [59].

11.7. Lianxiangyuan pilot project

A 200 Mbps BPL technology is employed in this project in order to obtain power consumption data. Interactive communication between the customers and the power grid is available Water and gas information are collected with wireless technology. This project has also dealt with home security system for making emergency calls, detecting gas leakage or smoke. BPL offers many advantages for the Lianxiangyuan project, such as video on demand, IP telephony and broadband access services 13]. Home appliances are managed by the PLC technology as well.

11.8. Pilot project in Yard 95, Fucheng road

The purpose of the project was to develop and use an interactive platform between the customers and the power grid. Many interactive services based on set-top boxes and televisions were offered by this project; smart home networking was made available in addition to getting the power consumption data.

Two master stations, a collecting and a community service one were used [13]. Other components of the system included a concentrator, two-way prepayment smart e-meters, solar power generation equipment connected to the grid, set top boxes, smart sockets and home security equipment [13].

12. Open issues and future work

PLC technology has a 'coexistence' problem. PLC spectrum is not well-shaped and the channel resources of PLC systems are used without interference prevention mechanisms. Although a good design can eliminate the interference between noninteroperable technologies separated in frequency, the performance degradation due to mutual interference need to be handled [46]. Therefore, the implementation of efficient coexistence mechanisms in PLC is a necessary future step to enable interference-free SG applications based on PLC.

Another open issue is the poor integration of PLC and IP technologies. IP protocol support is an important requirement for the establishment of PLC technologies in SGs. In addition, another two important requirements for SG applications, namely, the provision for real time communication and the enabling of high data rates, are still under development [63,64]. Real time communication is necessary in order to control the behavior of SGs. The quality of communication links in PLC networks can vary with time changes and switching operations can change the network topologies [65]. Therefore, when a fault occurs in the SG, the PLC system must react quickly.

At the current ongoing stage of the SG, choices encompassing a diversity of solutions and implementations should be made to deal with the complex problem of building SG applications [46]. Therefore, instead of using PLC alone, a heterogeneous set of networking technologies should be preferred. Finally, PLC networks are open networks that necessitate efficient security mechanisms; this is also an open research issue (see Table 12).

13. Conclusion

PLC technologies are well-suited for several SG applications because they provide low-cost and flexible communication networks for these applications. However, in their current state of matureness, PLC technologies are still faced with challenges such as security, real time communication and coexistence; further research work is necessary to address these issues efficiently. Numerous proposed standards, projects and products exist today in relation to PLC technology; the use of PLC for SG applications, however, is a new subject and is still being investigated. Based on the specific requirements of the target application, one or more of these are used together to better answer its communication requirements.

The goal of this study has been to present a detailed review of existing PLC standards, products and projects; moreover, to investigate the use of PLC technologies for SG applications. The findings might be summarized as follows: Although, in the recent years, PLC is clearly in use and certain standards have been developed for PLC-based SG applications (as presented in the body of this paper) major challenges still exist, calling for further investigation of important open research issues, such as the IP integration or the real time communication problems.

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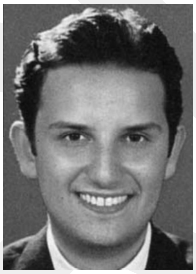

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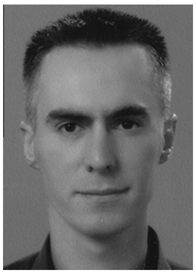

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