



Broadband Power Line Communication

In the last decade, BB PLC chips by semiconductor vendors, such as Intellon,²

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Power line communications

L. Lampe, L.T. Berger, in

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16.3.2 Regulations for Broadband PLC

The applicable EMC limits for BB [PLC](#) have been controversially discussed. Insightful accounts of the developments under the auspices of IEC's Comité International Spécial des Perturbations Radioélectriques (CISPR, International Special Committee on Radio Interference) and the European Telecommunications Standards Institute (ETSI) and CENELEC can be found in [91, 92, 96].

In Europe, EN 50561-1 [97] was approved in Nov. 2012. This standard “specifies limits and methods of measurement of [radio disturbance](#) characteristics for in-home communication apparatus that use the low voltage power installation as the transmission medium” and it applies to the frequency range 1.6065–30 MHz. It distinguishes between “AC mains power,” “telecommunications/network,” and “PLC” ports and specifies conducted emission limits and the corresponding measurement procedures. The standard requires a [dynamic power control](#), ie, the reduction of the maximal transmitter [power spectral density](#) (PSD) level for low channel attenuation between two PLC



notching for which the PLC equipment senses the presence of radio services and notches the affected frequencies for its own operation. At the time of writing, standard EN 50561-2 for “modems for access networks” has been sent out for comments to the National Committees. Furthermore, EN 50561-3 for “apparatus operating above 30MHz,” which clarifies the transmission levels below the FM radio bands, is currently still under development.

In the United States, again the 47 CFR §15 [94] regulates electromagnetic emissions for BB PLC. In the jargon of [94], these are “BPL” systems, and it is distinguished between in-house and access BPL. The former send “radio frequency energy on frequencies between 1.705 and 80MHz over medium [voltage lines](#) or over low voltage lines to provide [BB communications](#) and is located on the supply side of the utility service’s points of interconnection with customer premises,” while the latter use “electric power lines that are not owned, operated, or controlled by an electric service provider.” Both of them are subsets of carrier current systems. Hence, the paragraphs mentioned on the right-hand side of Fig. 16.6 generally apply. For access BPL, [94] includes a Subpart G, which further specifies that conducted emission limits are explicitly not applicable, BB [PLC systems](#) have to be able to notch certain frequencies that might be used by other services, excluding bands where no PLC signal shall be injected, as well as geographical exclusion zones close to which no access PLC systems may be deployed. Further, procedures in which service providers inform about prospective PLC access deployments, as well as complaint handling procedures, are a requirement.

The specific radiation limits are given in terms of [field strength](#) at a certain distance for BB PLC between 1.705 and 30MHz and between 30 and 88MHz, respectively. The latter distinguishes whether accessing PLC is over MV or LV lines, with an approximately 10 dB higher limit for the former. The translation of these radiation limits into [PSD](#) figures for PLC transmission is done via a coupling factor, which depends on a variety of factors related to topology, cabling, and symmetry of the power grid.

The application of BB PLC in [Japan](#) is limited to in-home power lines. The emission limits are specified for the 2–15 and 15–30MHz bands in terms of the common mode current measured with a specified impedance stabilization that features a longitudinal conversion loss (LCL) of 16 dB [98]. The LCL quantifies the differential-mode (from the PLC device) to common-mode (mainly responsible for radiation) conversion and it is argued in [96] that 16 dB is a 99% worst-case value for typical power line networks found in Japanese homes.



for the average [transmitter PSD](#) for BB PLC for the three regions discussed in this section. These limits are illustrated in Fig. 16.7. We note the general drop of PSD levels at 30MHz, which has been assumed

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Power line communication technologies in smart grids

Ersan Kabalci, Yasin Kabalci, in
[From Smart Grid to Internet of Energy](#), 2019

4.2.3 Broadband PLC

The success of the NB [PLC systems](#) encouraged development of the BB PLC systems, and primary application studies have been performed for internet access and HAN applications. The first application that aimed to enable Internet access to residential customers over power lines were developed by Nortel and Norweb Communications in Europe. The developed technology has been tested in a network composed of homes and schools, and >1 Mbps data rates have been achieved thanks to performed experiments [17, 36]. Unfortunately, the project has been terminated in 1999 due to cost and EMC issues. Other projects conducted by Siemens and Ascom experienced similar situations. The Open [PLC](#) European Research Alliance (OPERA) project that was funded by the European Commission provided significant improvements in the field of the BB PLC.

After the first unsuccessful period of BB PLC, home applications and industrial communication applications of BB PLC systems have become more popular for industrial areas in the early 2000s. The HomePlug, UPA, HD-PLC, and The HomeGrid Forum have played important roles for BB PLC systems. In 2005, HomePlug AV was proposed for indoor environments in order to enable multi stream networking with high quality feature. Depending on its advanced PHY and MAC layer characteristic, this standard is capable to achieve 200 Mbps data rates over AC power lines in-home networks. Therefore, it provides high quality broadband services containing audio, video and data over existing power lines of home areas. Furthermore, HomePlug AV can support High-Definition TV (HDTV) and Voice over Internet Protocol (VoIP) applications owing to ensuring high data rates. The most popular commercial devices are compatible with HomePlug AV and HD-PLC standard. The MAC layer of these devices exploits time-division

Entropic Communications, LLC, Exhibit 2013



been created based on the HomePlug AV and HD-PLC standard. In 2010, HomePlug Green PHY that has been released as a special type of HomePlug AV standard presents low cost and [low power consumption](#) features for potential SG applications. Specifications of popular BB PLC standards and technologies are listed in Table 4.2 [35].

Table 4.2. Standards, technical specifications and applications of the BB PLC systems [35]

Technology/standard	Spectrum	Modulation/coding	Bit-rate
HomePlug AV	1.8–30MHz	OFDM (with adaptive bit loading)/turbo codes	200Mbit/s
IEEE 1901	1–10MHz	OFDM (with adaptive bit loading)	500Mbit/s

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Power line communications and hybrid systems for home networks

M. Koch, in [Ecological Design of Smart Home Networks](#), 2015

2.3.1 Concept of PLC as backbone and available technologies

The concept of using [PLC](#) as backbone and connecting it to [wireless technologies](#) is motivated by different scenarios and combinations of them. For example:

1. The [wireless technology](#) is needed for connecting the terminal, whereas it has difficulties transmitting thorough floors or walls. Refer to Section 2.1 Introduction and Figure 2.1. For implementation in the home network, there are many broadband PLC-to-Wi-Fi 802.11 bridges available on the market. Usually, such a bridge is simply plugged into the mains socket.
2. The wireless technology is needed for connecting the gateway into the house, but the terminal is connected to PLC. A long-term evolution (LTE=fourth-generation mobile network standard) gateway with outdoor antenna and the distribution of the Internet signal inside the house is such an example. Technical



available.

3. A meter (e.g., gas meter, water meter) has no connection to the power grid, but the AMR should be processed through the same gateway as a power meter with PLC connection – either between private household and utility or inside the home to a central display (e.g., on a PC or smartphone). This meter usually offers a wireless interface. Depending on the region and/or the decision of the utility, the following three wireless technologies are the primary ones used for this application (bridges between each of these wireless technologies and many different PLC technologies are available on the market).
 - a. ZigBee

ZigBee has been developed by the ZigBee Alliance and standardized by IEEE 802.15.4. It can operate in different frequencies (depending on the region) and between 20 and 250kbit/s raw data rate. The ZigBee Alliance states that the transmission distance is between 10 and 1600m. With the present application scenario, **power consumption** is critical. as

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Role of power line communications in the Smart Grid: applications, challenges, and research initiatives

P. Muralidhara Rao, B.D. Deebak, in
[Sustainable Networks in Smart Grid](#), 2022

4.3.3 Communication standards

[PLC](#) is a communication technology that facilitates transmitting data over existing power cables. With the help of power cables fixing to an electric device, it can power up and retrieve the data from it in a half-duplex mode. According to the market strategy, PLC technologies have broadly classified into four categories:

1. Ultra-Narrowband PLC (UNB-PLC)
2. Narrowband PLC (NB-PLC)
3. Broadband PLC (BB-PLC)
4. Quasi band PLC (QB-PLC)

Narrowband PLC segments work at a lower frequency, that is, 3–500kHz, lower data rates 100kbps, and kilometers longer-range, and it



Narrowband PLC can also be used in smart energy generation, especially in microinverter for solar panels, an alternative energy source (Fenton, 2006).

In contrast, broadband PLC operates at a higher frequency, that is, 1.8–250MHz, high data rates, that is, more than 100Mbps, and is used in short-range applications, that is, below kilometer. Therefore, it mainly serves as a promising technology for internet distribution and home networking. With the benefits of higher data rates and lower wiring, broadband PLCs are becoming an effective solution for multimedia distribution technology for home networks. These features bring optimistic ways of attracting the market acquisition of various lead companies (Trl et al., 2014).

Alongside, PLC can be classified in another way is as follows:

1. PLC over AC line
2. PLC over DC line

Nowadays, most of the competitor companies pitched towards the development of AC line DC line PLC applications. Over DC, these PLC technologies can be used in electronic controls in planes, trains, and other vehicles, distributed energy generation in the transportation segment (Dell & Rand, 2001). PLCs in these segments can minimize wiring complexity, weight, and communication cost over the terminals and inside vehicles (Table 4.2).

Table 4.2. Communication technologies for Smart Grid.

Technology	Merits	Demerits
• Optical fiber	• High capacity • Stable characteristics	• High cost
• Wireless	• Cost-effective • Mature technology • Rapid installation	• Limited coverage • High capacity • Security • Reliability
• Satellite	• Global coverage • Rapid installation	• High cost • Long delay • Dynamic channel
• PLC	• Extensive coverage	• High noise



- | | |
|--|---|
| <ul style="list-style-type: none">• Available Infrastructure• Reliable• Cost-effective | <ul style="list-style-type: none">• Signal Attenuation• Cable loss and multipath• EMI |
|--|---|

4.3.3.1 Power-line telecommunications

It is a European Telecommunications Standards Institute (ETSI), establishes the essential voice and data transfer standards over

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Restructuring of Electrical Power Systems

P.S.R. Murty, in [Electrical Power Systems](#), 2017

25.4 Smart Grid Technologies

1. *Integrated Two-Way [Communication System](#)*: This is the most important aspect in developing a smart grid. The [communication system](#) includes the tasks of data acquisition, protection, and control and also provides for the user intelligent electronic appliances to interact with the [integrated system](#). Unified communication includes audio, video and data power line communication, broadband over power line, and distribution line carrier systems which operate on high-, medium-, and low-voltage lines respectively. [Wireless communication](#) system may involve, worldwide Interoperability for Microwave, (Wi Max), Wi-Fi, ZigBee, cellular, and so on.
2. *Sensors and Measurements*: Sensors predict peak load issues and utilize automatic switching to divert or reduce power at predetermined strategic locations on the network so that the chance of overload is eliminated or reduced and the occurrence of supply disconnection overcomes. [Advanced metering infrastructure](#) (AMI) increases the range for time-based rate programs. These time-based rate programs permit smart customers to change their demand patterns and reduce their own power bills as well as reduce the peak demand on the system. Various measurements, which are the outputs of the sensors, are utilized to assess the health and integrity of the grid continuously. Automatic meter



3. *Advanced Components*: The successes in fundamental research and development in areas of power electronic and microelectronic devices, superconducting materials, and chemistry will determine the success and affordability of smart grid to a greater extent. The advanced components and devices will have to enable the complex functions required to be performed by a smart grid reliably.
4. *Advanced Controls*: Continuous analysis, diagnosis, and prediction of the grid conditions and initiation and completion of appropriate

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Smart Grid Communications: Opportunities and Challenges

Hussein T. Mouftah, Melike Erol-Kantarci, in
[Handbook of Green Information and Communication Systems](#),
 2013

25.3.2.1 Power Line Communications

Power line communications (PLCs) use the low voltage power lines as a communication medium for data. [PLC](#) has been already used by some utilities for load control and remote metering. It is simply integrated to the smart metering system since the power lines already reach the meter [36]. As the PLC does not have external cabling cost, it is considered to be convenient for HANs, NANs, and FANs [37].

PLC technology has been initially operating in the narrowband, and it has evolved into broadband according to the needs of consumer applications. Broadband [PLC systems](#) operate in the 230MHz band and can achieve data rates up to 200Mbps [15]. There are a large number of PLC standards that have evolved in time. Presently, three standards have been selected by NIST for possible adoption in the smart grid. These standards are IEEE P1901, ITU-T G.Hn, and ANSI/CEA 709 [13].

IEEE P1901/broadband over power lines: IEEE P1901 is a broadband over power lines (BPLs) standard that has been recently completed. BPL has high data rates exceeding 100Mbps using frequencies below 100MHz. Although it can operate around 30MHz and achieve higher data rates, high attenuation at low frequencies limits the range of communication, therefore it is not preferred.

The P1901 workgroup has selected two physical layers for the standard. One is the wavelet OFDM-based PHY and the other is the FFT OFDM-based PHY. These PHY techniques aim to improve communication over



specification [15]. IEEE P1901 is able to support more than 2000 devices.

ITU-T G.hn: ITU-T developed the G.hn standard for communication in residential premises, small-scale offices, hotels, and conference rooms [38]. G.hn is able to operate over all types of in-home wiring including phone line, power line, [coaxial cable](#), and Cat-5 cable. G.hn can support bit rates up to 1 Gbps. It uses a windowed OFDM-based PHY with a programmable set of parameters. These parameters give the G.hn standard the flexibility to operate over multiple media. G.hn supports up to 250 nodes. G.hn devices aim to be interoperable with power line devices that use the IEEE P1901 standard.

ANSI/CEA-709: The ANSI/CEA-709 series of standards have been developed for home control and automation. The ANSI/EIA 709.1 standard, which is also known as Lonworks, became an international standard in 2008. The Lonworks platform is a family of hardware components and software tools that are based on these standards. The platform is a proprietary technology of Echelon Corp. and it is relatively an old platform that has been competing with BACnet on building automation and control since the mid-1990s. Lonworks operates in the

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Power Systems Smart Power Engineering

Matias A. Kippke, in
[Encyclopedia of Electrical and Electronic Power Engineering](#),
2023

Analysis of communications infrastructures

Several communication infrastructures may be proposed that could fulfill the previously enumerated requirements. It is important to remark that there is no perfect solution to the data collection paradigm network. Instead, not only a plethora of communications protocols are considered, but also a whole set of connections between devices. Several questions arise regarding the feasibility of each one of the proposed solutions, but the key relies on the capacity of the



Wired connections for data collection

If flexibility is postulated as the unique [feasible solution](#) to address electrification without incurring unbearable costs, then communication infrastructures for data collection should follow that premise as well. The first approach thus will be to consider the already-existing [distribution network](#) not only to exchange power between bi-directional devices and the grid but also to interconnect metering devices with each other. This translates as reduced costs in deployment (given the fact that the network is already made, and it is just a matter of reusing already-existing infrastructure) and a simpler approach to the implementation matter in the flexibility scalability problem.

[Power Line Communication](#) (PLC) infrastructure is therefore considered the most suitable solution to reduce deployment costs. Together with Device Language Message Specification/Companion Specification for Energy Metering (DLMS/COSEM), PLC communication describes the physical layer on the 7-layer OSI model, with different implementations according to the available bandwidth:

- Ultra-Narrow Band PLC (UNB-PLC): Packed with an extremely constrained data rate capacity of around 100 bits-per-second (bps), UNB PLC extends in the 0.3 and 3 kHz frequency spectrum.
- [Narrow Band](#) PLC (NB-PLC): Normally implemented in the CENELEC-A band comprehending the frequency spectrum between 3 kHz and 148.5 kHz, it has been proposed as the standard to follow by the Powerline Related Intelligent Metering Evolution (PRIME) protocol for smart meter's data collection. Measured data rates are about 125 kb/s.
- BroadBand PLC (BB-PLC): With enhanced data rate capability given the use of **high-frequency** and very-high frequency spectrum ranging from 1.8 MHz to 250 MHz, could be the feasible solution for enhancing smart meters' capabilities of transmitting data in real-time for AMIs modern development.

Even though PLC emerges as the only wired approach solution with costs comparable to new wireless network designs (Galli et al., 2011) there are certain limitations that this technology cannot overcome.

Firstly, given local regulations in several countries, the CENELEC-A band is the only suitable communication frequency allowed in every territory. This implies that to achieve full-scale deployment for several customers, data rates and reliability are constrained to this specific band behavior. Not suitable for real-time deployments, only averaged-hourly data is available using this type of communication (Hashmi et al., 2022). The new implementation of the PRIME 4 protocol proposes



results have been yet tested in a laboratory environment. Thus, these limitations do not allow participation in a real-time flexibility scheme, thus constraining the quality of the [ancillary](#) services that can be provided. Even more, the PLC communication channel is often modeled as a highly [noisy environment](#) packed with harmonics generated by different electric loads. Therefore, communication may be compromised, and individual cases for each vendor should be analyzed separately, thus compromising also large-scale deployments of AMIs.

Considering wireless LLN networks

The only feasible approach for a wired communication infrastructure is based on the well-known Ethernet/TCP-IP protocols. Nevertheless, such a proposal implies a significant increase in deployment cost (aka known as capital expenditure, or CAPEX) and does not cope with the constrained power requirements, thus relying on higher budgets.

Wireless approaches are considered as a compromise solution between expenditure, constrained power applications and ensuring reliability in low-power and lossy networks (LLNs). If the CENELEC-A band was modeled as a noisy communication channel, open-air communication often suffers from high [packet loss probability](#). Nevertheless, the wireless approach also implies a reduction in deployment costs since the network does not rely on a physical connection. Different areas of implementation should also be considered, based on each specific application as depicted in Fig. 3.

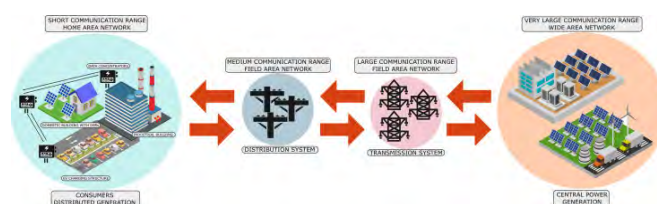


Fig.3. Communication areas considering application ranges.

Source: own production, published in Arboleya et al. (2022).

Star-type topology: LoRaWAN

Regarding low-power implementation, Low Power Wide Area Networks (LoRaWAN) propose a revolutionary approach by implementing a certain type of modulation in a spread waveform solution, also called Chirp Spread Spectrum (CCS). Enhancing the range of applications, also implies the interconnection of a large number of nodes in scattered areas, with an appropriate data bandwidth. Nevertheless, the star-topology approach implies a certain risk, as the probability of failure increases linearly with the number of devices and the data concentrators/gateways being deployed. Consequently, other types of [network topologies](#) could also mean a better approach for [IoT](#)



The lack of support for the newly developed IPv6 protocol also implies that deployment is limited and highly relies on the adaptation layers provided by LoRa gateways to take part in communication with already

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Smart metering and smart monitoring systems

Ersan Kabalcı, Yasin Kabalcı, in
[From Smart Grid to Internet of Energy](#), 2019

2.3.2 Communication interface

The communication networks of a smart meter should comply with two-way data transmission needs of smart grid infrastructure. The two-way communication concept defines mutual connection procedure between all sides of customer and network operators. Therefore, the installed communication medium should ensure bidirectional data transmission between customers and network operators in addition to customer-network operator channel. The communication module of smart meters is equipped with several types of communication technologies and operates independent from AFE and recording sections of smart meter. Thus, an error occurred on connection module does not cause any disruption on smart meter functions. The communication interface of smart meter includes wireline or wireless transmission technologies as discussed earlier. Moreover, the communication technologies should cooperate with network architectures such as HAN, NAN, and WAN as depicted in Fig. 2.4 where area networks are based on many protocols and services on layer structure for ensuring secure and reliable communication. The layer structure of any network is comprised regarding to some standards that most widely accepted on is open systems interconnection (OSI) model comprised by seven layers. The initial layer of network architecture is physical layer (PHY) that is responsible for electrical, physical and [optical transmission](#) of data as its name implies. The second layer known as [data link layer](#) where [medium access control](#) (MAC) provides direct connection between two nodes and corrects erroneous data transmitted by PHY layer. The [MAC](#) layer enables Ethernet, IEEE 802.11 Wi-Fi, IEEE 802.15.4 and ZigBee type communications to operate at the data link layer. The third layer of OSI conceptual model is network layer that is responsible for ensuring



architecture comprise the smart grid. Therefore, network layer enables each node with an address and communication technology to operate on the same area network [2, 10].

The utility grid requires a smart metering network including high and low bandwidth sections if we recall Fig. 2.4. The WAN meets high [bandwidth requirements](#) with its huge number of communication channels and connections with [data concentrators](#) and gateways. The communication networks that are used in smart metering are classified into three groups as shown in Fig. 2.7 and communication technologies are listed under each area networks with their network layer interaction.

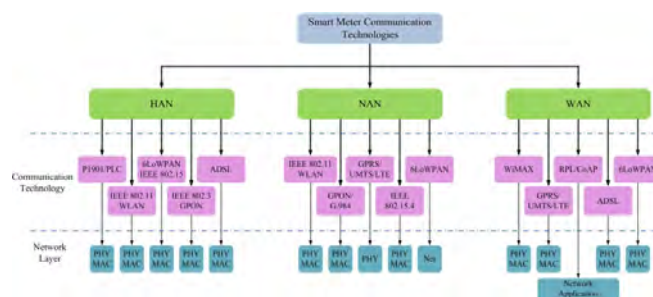


Fig. 2.7. Communication technologies and network layers used in smart meters.

2.3.2.1 Home area network

HAN is the fundamental network architecture deployed at customer premises to monitor and control integrated devices and to perform smart metering processes. It integrates many devices such as [HEMS](#) associated smart appliances, smart meters, smart sockets and plugs, and [PEVs](#). HAN facilitates interaction of [energy management systems](#) and smart appliances to improve control and comfort of users and network operators. One of the most important benefits of HAN for [TSO](#) and DSOs is to enable DSM by establishing a two-way communication infrastructure for smart meters. Another important contribution of HAN is its capability to get connected to outer world by NAN interactions.

A wide variety of technologies including [PLC](#), IEEE 1901 broadband over power lines (BPL), ITU-T G.984 gigabit [passive optical network](#) (GPON), IEEE 802.3ah ethernet passive optical network (EPON), IEEE 802.11 wireless local area network (WLAN), IEEE 802.15.1 wireless [personal area network](#) (WPAN), IEEE 802.15.4 low rate WPAN (LoWPAN) and [asymmetric digital subscriber line](#) (ADSL) comprise the heterogeneous environment of HAN architecture as common communication technologies.



Internet based infrastructures can be used in the context of BPL connections for wireline communication of first mile and last mile devices. The fundamental benefit of wireline communication is its reliability and robustness against interference. The ADSL and fiber [optic technologies](#) including GPON and EPON are also widely used besides PLC in wireline [communication systems](#). The [data transmission rates](#) of DSL line vary between 10Mbps and 10Gbps while fiber optics extends these ranges up to 160Gbps. Two major PLC technologies that are [narrow band](#) PLC (NB-PLC) and broadband PLC (BB-PLC) are classified according to their transmission frequencies.

The NB-PLC can be used in low and high voltage line up to 150km transmission length and operates up to 500kHz transmission frequency. On the other hand, BB-PLC allows high data transmission rates up to 200Mbps and high transmission frequencies up to 30MHz [2, 13]. Regardless of wireline or wireless, the communication technologies interact with HAN over PHY and MAC layers.

2.3.2.2 Neighborhood area network

The NAN is located between HAN and NAN to serve as a central bridge of smart metering infrastructure devices. The NB-PLC can be used in low and high voltage line up to 150km transmission length and operates data transmission through HAN and [WAN systems](#). In addition to communication technologies that are used in HAN, there are several additional technologies are used in NAN networks for communication. NAN allows use of open standard to increase reliability, security, interoperability and flexibility of system. Moreover, NAN enables internet-based communication technologies to be used in architecture. The transmission rate of [wireless communication](#) can be extended up to 1Gbps by the contribution of IEEE 802.11 WLAN. The MAC based LoWPAN enables to communicate in 868MHz, 902–908MHz, and 2.4GHz license free bands. The IEEE 802.15.4 standard is a basis for ZigBee that is a low-cost and easily integrated device for smart metering applications. Moreover, several cellular technologies such as [universal mobile telecommunications system](#) (UMTS) and long-term evolution (LTE) are used in communication architecture of NAN and

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telecommunication technologies for Smart Grids: Total Cost Optimization

Marcelo Eduardo Vieira Segatto, ... Marco Antônio do Rosário Santos Cruz, in

[Advances in Renewable Energies and Power Technologies](#), 2018

14.4.3 Broadband Data Communications Over MV Powerlines

[Power line communications](#) are an attractive technology to transport the smart meter aggregated information acquired by home area networks, without the elevated cost and implantation time required by the well-known solutions based on wireless and [optical fibers](#). Indeed, as a neighborhood area network, the broadband power line (BPL) appears as a good candidate for data communication due to the already installed and pervasive power distribution infrastructure [8] [9].

The [PLC](#) idea emerged in 1838, when a remote measurement system was proposed to monitoring [battery](#) levels of sites far from a telegraph system. The first carrier frequency system began to operate over high-voltage lines in the frequency range of 15–500kHz for telemetry applications in 1922. The first system designed to work over MV and low-voltage (LV) electric networks was used for remote switching of public lights and tariff changes in 1950, employing a carrier frequency between 100Hz and 1 kHz in a one-directional communication established via control signals [10]. Later, bidirectional narrowband [communication systems](#) were designed for applications such as control and telemetry of electronic devices, dynamic tariff control, load management, and load profile recording. Nowadays, the PLC technology has been enhanced, bringing improvements in transmission speed, security, and service quality, providing high performance transmission for broadband services such as video streaming, internet, and cloud access [11].

However, impairments generated by the high selectivity observed in its channel frequency response, by impulsive noise and by frequency interference due to radio broadcasters and electric devices connected in the same network, represent some challenges to overcome for convenient BPL communications [12]. [Distribution networks](#) at MV levels composed of overhead multiconductor transmission lines can be used not only for remote metering but also for real-time bidirectional high data rate applications in a treelike topology as shown in Fig. 14.9 [13]. Interference and impulsive noise over MV distribution power lines are not so powerful when compared with the LV grid, due to the quantity and type of electric connected devices [13]. For this reason,



industries and academic communities.

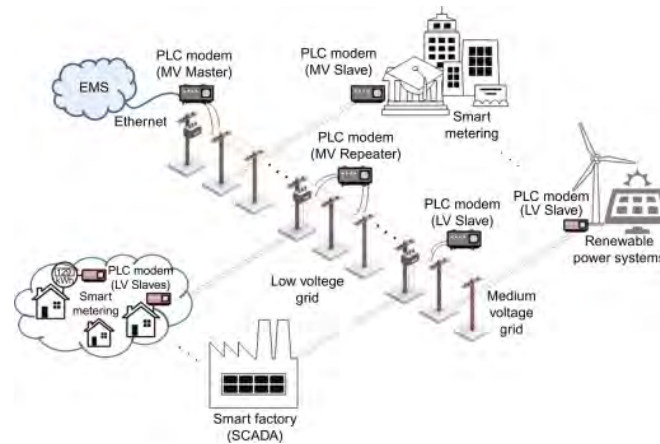


Fig. 14.9. Broadband power line communication as a PLC solution for interconnection in smart grid neighborhood networks.

The broadband power line network showed in Fig. 14.9 consists of a number of terminal users that transmit/receive information in a shared medium to/from a centralized station. In a long-reach network, with different devices connected to the same master equipment, repeaters can be inserted in order to increase the coverage. In a typical treelike PLC topology, a central master node concentrates and commands all of the upstream and downstream traffic in the network [14]. Normally, it assigns resources to all nodes of the BPL cell through the use of a token, according to [QoS](#) requirements.

A repeater acts as a master node, sharing its allocated channel among their slave nodes according to the traffic flows, the service class and the origin/destination. Therefore, it will be the slave of its master, which can be a centralized master or another repeater, and the master of its slaves. The LV and/or MV slaves are the equipment's installed close to the smart metering, power stations, smart factories, and customer's household. A slave must subscribe to the network before being able to access the channel, which means that it must select a master that assigns a channel [access time](#). A validation process should be executed by the masters in order to validate the slave as a network unit [15].

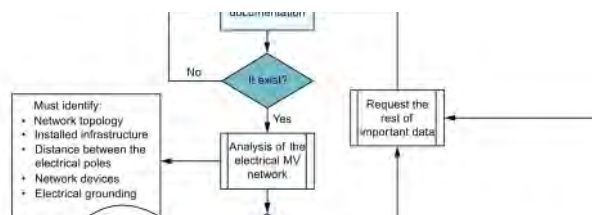
The communications over the electric power supply networks have been improved along the years. Standard organization, consortiums, and associations such as the European Telecommunications Standards Institute-power line telecommunications (ETSI-PLT), the HomePlug Powerline Alliance, the Institute of Electrical and Electronics Engineers (IEEE) BPL study group, POWERNET, Open PLC European Research Alliance (OPERA), and the Universal Powerline Association (UPA) emerged for the development of this technology. Nowadays, a BPL equipment, able to transport broadband service over a power grid in a



uses optimized techniques for coding, modulation, and [error correction](#), resulting in excellent connectivity between BPL devices and data rates up to 200Mbps over this frequency range [9] [10].

One of the most significant characteristics of PLC channels is its frequency selective due to reflections caused by impedance mismatches. The overhead MV power line grid also exhibits attenuation and low-pass behavior that limits the bandwidth that shall be used in the communication. Moreover, the time-varying phenomenon occurs due to changes in the topology, cables, and connected loads. To overcome those drawbacks, orthogonal frequency-division multiplexing (OFDM) techniques have been implemented in some BPL equipments, with its inherent adaptability in the presence of [frequency selective channels](#), its robustness to impulsive noise, and [high spectral efficiency](#). Among its several [subcarriers](#), OFDM can employ different [modulation levels](#) in an adaptive mapping, after channel estimation through pilot symbols, in order to maximize channel capacity [10] [12].

A useful methodology for design and implement the BPL technology in MV power lines is obtained from the flowchart showed in Fig. 14.10. Beyond the features implemented in some modern equipment, it considers that repeaters should be used if BPL link distances exceed 400m [15].



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Sensing, communication and security planes: A new challenge for a smart city system design

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5.6 Power Line Communication (PLC)

[Power Line Communication](#) (PLC) refers to techniques that utilize the existing electric power lines as a communication medium. [PLC](#) can provide either reliable narrowband (below 500kHz) or high-speed broadband (up to 100MHz, reaching data rates as high as 1Gbps) connectivity for many [IoT](#) applications[276]. In deployment areas where the required power line infrastructure already exists, PLC can outperform many [wireless technologies](#) in terms of reliability and cost. Additionally, it can readily pass through obstacles and reach enclosed indoor environments[277]. In this section, we overview some of the most notable efforts undertaken toward PLC implementations.

5.6.1 IEEE 1901-2010/ IEEE 1901.2

IEEE 1901-2010 technology is a broadband (BB) PLC technique, designed particularly for multimedia home traffic and select [smart city applications](#) such as smart grid and Automatic Measuring Infrastructure (AMI). IEEE 1901-2010 operates in the 2–30MHz frequency band and can deliver throughputs up to 500Mbps. This technology is developed for low and medium voltage [power transmission lines](#) and is not compatible with Digital Subscriber Line (DSL) or coax cables. The overall architecture of the network includes a service provider, which typically provides a single *Access Network (AN)* over a specific PLC infrastructure. An AN can be divided into multiple *cells* (or equivalently, [Basic Service Sets](#)). Each cell consists of one or more stations (STAs), *Repeaters (RPs)*, *Network Termination Units (NTUs)*, and a single *Head End (HE)*. STAs within a cell can communicate with



Considering that the maximum distance a signal can travel over power lines is determined by various—and uncontrollable—parameters such as noise, medium quality, and even weather, IEEE 1901-2010 uses RPs to regenerate and re-transfer packets, thereby increasing the coverage of the network. NTUs bridge IEEE 1901 PLC communication with other *In-Home (IH)* networks such as WiFi and Ethernet. The number of cells in an AN is typically determined by the [QoS](#) requirements of STAs, where STAs with the same QoS requirements must be grouped in the same cell[278]. Only PHY and MAC layers are specified in IEEE 1901-2010. The PHY level uses either [Fast Fourier Transform](#) (FFT) OFDM or Wavelet OFDM. The MAC layer allows both synchronous and asynchronous medium access, based on TDMA and CSMA/CA mechanisms, respectively. In an AN, HEs are assigned a 6-bit Short Network Identification (SNID), allowing a total of 63 to be defined (SNID zero is reserved). Similarly, a 12-bit Terminal Entity Identification (TEID) is used to address STAs. Therefore, over 4000 Stations can be defined in a single cell[279]. For applications that do not require [broadband connectivity](#), IEEE 1901.2 is a narrowband PLC alternative, which can provide data rates as high as 234kbps[280]. This technology was first standardized in 2013 and it operates in the 10–490kHz frequency band (in the US) and uses OFDM modulation to improve robustness against noise. Similar to IEEE 1901.1, IEEE 1901.2 is compatible with low voltage (≤ 1 kV) and medium voltage (between 1 kV and 73 kV) power lines. Only PHY and MAC layers are specified in this standard. The latter is based on IEEE 802.15.4-2016 and uses the same CSMA/CA medium access mechanism. However, various modifications are included to improve efficiency and add priority-based medium access.

The primary strengths of the IEEE 1901-2010 protocol are its extended coverage, reliable communication over a non-reliable power line infrastructure, and impressive throughput. Additionally, this protocol is capable of supporting thousands of nodes, which addresses the [scalability requirement](#) of smart city applications. Furthermore, this technology can be used in a wide range of topologies such as mesh, tree, ring, and hybrid. Utilizing both CSMA/CA and Transmission Opportunities (TXOPs) provides the foundation for QoS diversification, thereby addressing the QoS heterogeneity requirement of smart city applications. STAs can coordinate their medium access with their associated HE to receive *differentiated* and *reserved* access, which allows prioritization of STAs based on the application. However, only two priority levels (high and normal) are defined to avoid complicating the network[281].



1901.2 can cater to applications that value simplicity and cost reduction. Utilizing the MAC layer of IEEE 802.15.4-2006 makes IEEE 1901.2 compatible with 6LoWPAN, thereby adding IPv6 compatibility to the protocol[282]. However, unlike IEEE 802.15.4, this standard includes modifications to include both ACK and NACK packages. Furthermore, [Automatic Repeat Request](#) (ARQ) is also implemented to improve reliability.

IEEE 1901-2010 suffers from multiple drawbacks. First, 500Mbps throughput is proven to be unnecessary for many [AMI](#) and [smart grid applications](#). Therefore, a substantial gain could be achieved by trading off the throughput for simplicity, power consumption, and cost. Additionally, limiting the compatibility of IEEE 1901-2010 to low and medium voltage power line infrastructures restricts its applicability to environments with an existing Coax or DSL infrastructure[283]. Although priority-based medium access techniques are effective against high latency in delay-sensitive applications, they can potentially lead to resource starvation for nodes with lower priority[277]. Despite great opportunities to substantially enhance the MAC layer efficiency (through adjusting medium access contention parameters, as discussed in[284]), the performance of the network is known to decrease as the number of STAs increases. IEEE 1901.2 does not support multicasting, which reduces its energy efficiency.

Both IEEE 1901 and IEEE 1901.2 are developed particularly for applications such as smart grid, AMI, and electric vehicles, where power line infrastructure is assumed to be available. The high throughput of IEEE 1901 and its good coexistence for in-home networks also make it a good candidate for home and building automation. Due to the inherent characteristics of wired networks, applications of PLC technologies remain limited to stationary and static networks. Underlying characteristics of these two technologies are tabulated in Table8.

Table 8. A summary of Power Line Communication (PLC) technologies and their applications in smart city arena. *Example applications* includes example implementations or suggested applications of this technology.

Technology / Characteristics	Advantages/ Disadvantages	Example Applications	Suggested Application
IEEE 1901 (IEEE 1901.2) / 2–30MHz (10–490kHz)	Various Available Data Rates	Home Networks[278] Smart Lighting[281]	High Traffic Delay-Tolerant Networks (Multimedia

Entropic Communications, LLC, Exhibit 2013



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