1 Introduction

1.1 Motivation and Goals

Enterprise and residential buildings are facing an explosion in connectivity demands for high-bandwidth applications and automation. Networking infrastructure needs to be scaled to satisfy such demands and to provide reliable, full coverage for myriad devices and applications. Although wireless communications are pervasive and their efficiency has been largely improved by recent amendments to IEEE 802.11 standard, wireless networks often face coverage and congestion problems due to a limited unlicensed spectrum, thus failing to guarantee high quality of service to the end user. Nowadays, we observe an explosion of connectivity demands in all kinds of environments, from residential and enterprise to rural and urban, which is a challenge for state-of-the-art networking solutions. In addition, many applications have multiple requirements from communication technologies, such as mobility, ease of use, performance, and reliability. Performance can often be measured by throughput, which is the number of data bits delivered to the device by the network per second, or latency, which is the total time required to transmit data (e.g., a packet) from the moment it enters the transmission queue. Both throughput and latency depend on multiple network layers and are typically measured and characterized as the quality of service (QoS) of the application.

Wireless communication is dominant in residential and enterprise networks; it offers mobility and attractive data rates. Nevertheless, it often leaves “blind spots” in coverage due to building architecture. Wireless signals can be attenuated by walls built of brick or stucco, which act as an obstacle to network access for certain users. A study in 1000 American residences suggests that 40 percent of them have experienced problems with the wireless routers in their networks [1]. Among those households experiencing connectivity problems, 63 percent continue to have these problems despite some efforts to resolve them. One common solution is to incorporate wireless repeaters and to enable multihop communication. Yet, wireless signals are still obstructed by construction obstacles, often failing to extend coverage reliably.

Owing to the shared nature of wireless media, another connectivity issue arises from neighboring networks that cause interference to each other. This is usually addressed by assigning a frequency channel that is noninterfering with neighboring networks. However, channel allocation is becoming increasingly challenging, first, because of the density of wireless networks in urban environments, and second, because of recent Wi-Fi standardizations, such as IEEE 802.11ac/ax, that maximize utilized bandwidth (e.g., to 80/160 MHz), resulting in very few available noninterfering channels.

In addition to wireless signal attenuation and interference, there can be connectivity disadvantages with wired technologies like Ethernet. For instance, smart static devices, such as TVs or network drives, often enable only Ethernet connectivity, which requires costly infrastructure. Even when static devices offer Wi-Fi capabilities, users often prefer wired connections for nonmobile applications to avoid wasting Wi-Fi bandwidth. Compared to Wi-Fi, Ethernet usually does not have good coverage, and the ease of use is limited due to long wiring and high cost.

Wireless networking problems are exacerbated by congestion created by the number of connected devices. In recent years, a vast number of mobile devices has been added in everyday life: smartphones and tablets; wearables; and automation devices for comfort, energy savings, and security. In fact, Cisco estimates that by 2030, we will have more than 500 billion connected devices [2]. The explosion in the number of connected devices per building and the Internet of Things (IoT) networking require communication technologies and protocols that can scale and that react efficiently to congestion.

Beyond IoT and smart devices, wide bandwidth and decreases in processing costs enable many bandwidth-hungry applications, such as augmented reality, ultra high-definition streaming, gaming, video and web conferencing, cloud storage, and virtual desktops. Under increased bandwidth demands, Wi-Fi might fail to meet the required quality of service in case of multiple applications or contending flows, despite the recent amendments for high efficiency. These amendments have pushed most Wi-Fi parameters to the capacity limit (e.g., channel bandwidth, modulation, number of antennas and spatial streams). Hence, in the future, Wi-Fi capacity improvements will be limited. Moreover, as mentioned earlier, wired Ethernet technologies – often the most popular substitute for Wi-Fi – require costly infrastructure, confining their ubiquitous coverage. For all these reasons, additional communication mediums are required for bandwidth-hungry applications.

The aforementioned connectivity problems and demands call for hybrid networks combining multiple efficient and user-friendly communication technologies. The incorporation of additional communication technologies to today’s networks can bring multiple benefits. In addition to bandwidth aggregation, diverse mediums can augment network reliability, extend coverage, and provide different levels of quality of service in the network. Multiple technologies enable an exploitation of medium diversity and accommodation of more users and applications. This will enable the user to eliminate connectivity problems and meet high rate demands, in addition to resilience, a reliable backbone, and security.

In this book, we explore a promising communication technology for hybrid residential and enterprise networks: power line communications (PLC). PLC is beneficial in terms of both easy installation and high data rates: it enables data transmission via the electrical wires and through common power outlets – a ubiquitous infrastructure; it is trivial to install, as it does not require new wiring; and it provides rates up to 1.5 Gbps. Most common applications of PLC include Wi-Fi coverage extension and replacement of costly Ethernet connections, as depicted in Figure 1.1.

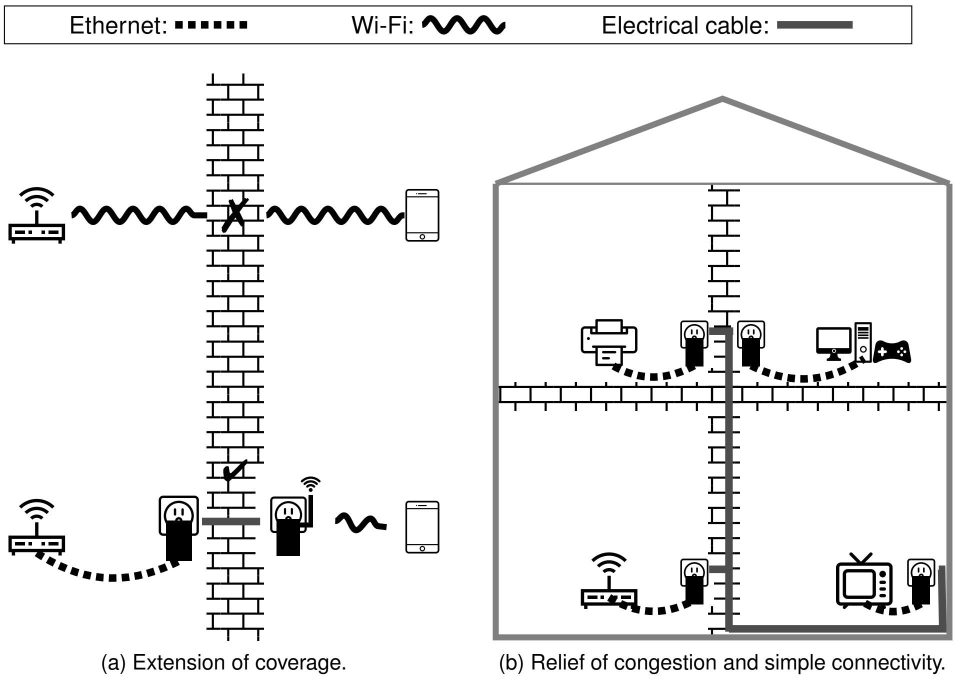

Figure 1.1 Examples of PLC addressing connectivity problems and demands. The icons of this book have been made by Freepik from `www.flaticon.com`.

The first goal of this book is to show the fundamentals of PLC in terms of channel characteristics, physical (PHY) and medium access control (MAC) layer functions, security, and performance. Second, the book provides guidelines to configure PLC devices, measure statistics, ensure security in data transmissions, and troubleshoot performance. To this end, we present a performance evaluation using the guidelines introduced in this book, pointing out the advantages and challenges of PLC, of which users and administrators should be aware.

In the remainder of this chapter, we first explore the evolution of hybrid networks and the candidate technologies for augmenting network reliability. We then turn our attention to power line communications. We discuss high-bandwidth and IoT PLC applications, standardizations, and specifications. Finally, we present the book's organization.

1.2 Local Networking Technologies

We discuss the state-of-the-art efforts for combining multiple communication technologies into heterogeneous (or hybrid – the two terms are used interchangeably) networks. Wi-Fi is always included in hybrid solutions, as it offers mobility and serves the vast majority of mobile applications. We explore candidate technologies that have the potential to augment Wi-Fi reliability, and we discuss their benefits and drawbacks.

As the demand for combining noninterfering technologies increases, new specifications for hybrid networks have been developed, such as the IEEE 1905.1 standard, which specifies abstraction layers for topology, link metrics, and forwarding rules [3]. Hybrid networks operate at layer 2.5, that is between IP and MAC layers, according to standardization and commercial solutions. In this way, they provide seamless connectivity and interoperability between different mediums, as the applications work above the Internet Protocol (IP) layer. Figure 1.2 shows the IEEE 1905 layers within the TCP/IP stack. As we observe, applications run on top of transport layer protocols, which are typically UDP (user datagram protocol) or TCP (transport layer protocol). The transport layer uses the IP for end-to-end addressing, routing, fragmentation, and other functions. The convergent layer of 1905 provides a single interface to the IP layer, resulting in seamless operations, irrespective of the lower layers.

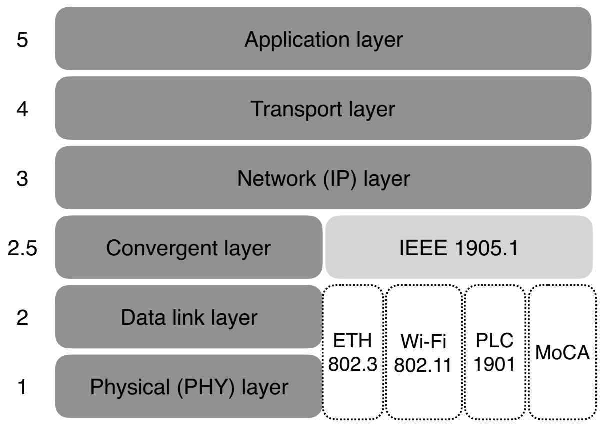

Figure 1.2 IEEE 1905 layer in the TCP/IP stack.

IEEE 1905.1 provides a common interface for widely deployed home networking technologies, such as wireless, power line, coaxial, and Ethernet communications. PLC, Wi-Fi, Ethernet, and coaxial (MoCA) technologies are defined and operate on layers 1 and 2 (physical and data link layers) of the TCP/IP stack, lower than the convergent layer of IEEE 1905, as we see in Figure 1.2. The MAC layer is one of two sublayers of the data link layer in the TCP/IP stack (the other sublayer is called logical link control). Multiple vendors have released hybrid products combining PLC and Wi-Fi or coaxial communications and Wi-Fi. In addition to reliability, full coverage, and bandwidth aggregation, IEEE 1905.1 targets energy management, simple and push-button security, and advanced network diagnostics. We describe the IEEE 1905.1 standard in Chapter 8.

Several candidates for enhancing Wi-Fi performance are on the market, among which are power line and coaxial communications. We now review these technologies in the quest for reliable, cost-effective, and easy-to-use communications. Table 1.1 summarizes the advantages and disadvantages of four popular communication technologies. We discuss each technology separately.

Table 1.1 IEEE 1905.1 candidate technologies for hybrid networks

Technology	Advantages	Disadvantages
Wi-Fi	Mobility and ease of use	• Prone to interference • Walls cause severe attenuation
PLC	High availability of outlets and ease of use	• Prone to interference • Performance varies depending on wiring quality and electrical grid structure
MoCA	High performance and reliability	Requires wiring and infrastructure
Ethernet	High performance and reliability	Requires new wiring and infrastructure

Wi-Fi is undoubtedly the most popular solution due to the explosion of mobile applications. The other candidate technologies often act as coverage extenders for Wi-Fi. The main reasons for the existence of these extenders are the connectivity demands and problems discussed in Section 1.1. In recent years, multichannel Wi-Fi is widely employed, with multiple Wi-Fi devices simultaneously utilizing channels in the 2.4 GHz and 5 GHz bands (such routers are called dual-band). The advantage of such solutions is mainly bandwidth aggregation; coverage extension and resilience are more challenging when using only two Wi-Fi bands, as all wireless band capacities are affected by similar correlated factors (e.g., signal penetration, mobility, fading). 60 GHz Wi-Fi is also being developed and offers multi-Gbps capacities, but its short range and blockage due to the human body prevent 60 GHz Wi-Fi from being a candidate for coverage extension.

PLC is becoming very popular in home networks. The main advantage of this technology is the no-new-wires connectivity and the high density of electrical plugs in any residential or enterprise environment. Furthermore, PLC is a natural and trivial solution for smart electrical appliances already connected to the grid. The potential disadvantages of PLC are interference – because PLC is a shared medium like Wi-Fi– and high performance variability depending on the age of the electrical grid or the electrical appliances operating, which affect the channel quality. Because of the similarities between wireless and power line media, many PHY/MAC layer techniques from Wi-Fi can be reused for PLC.

Coaxial communication is specified and designed by the Multimedia over Coax Alliance (MoCA) [4], and it is usually known simply as MoCA. Communication over coaxial cables achieves 1.4 Gbps data rates, using bands in the frequency range of 500–1650 MHz and with 100 MHz bandwidth. The main advantage of this technology is high reliability with packet error probability of about 10^{-6}. The interference is also limited to within the local network, as shielded coaxial wires prevent interference from neighboring households or other technologies. MoCA applications mainly focus on multiroom digital video recorders, over-the-top streaming content, gaming, and ultra high-definition (HD) streaming. Although it provides high reliability and rates,

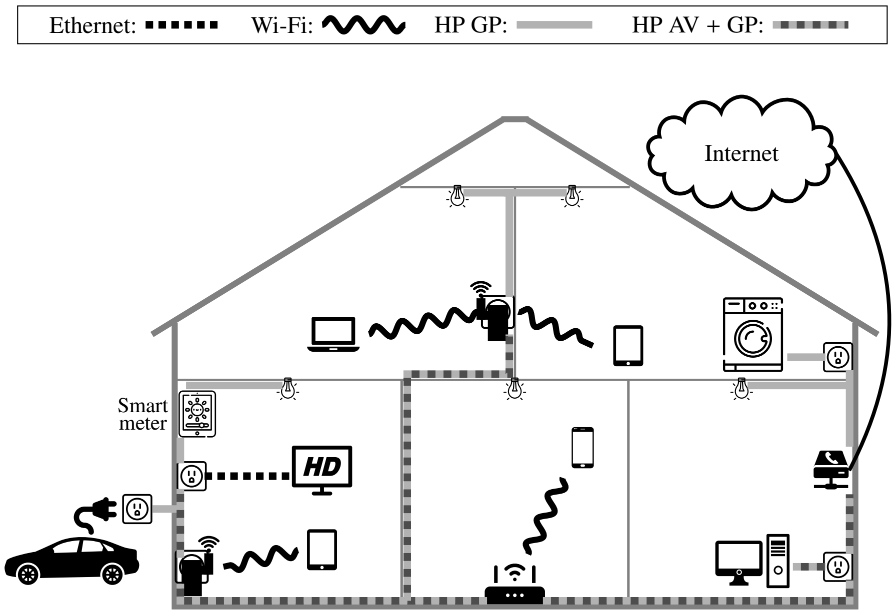

Figure 1.3 Connected home with PLC technologies: HomePlug AV/AV2/AV500 (HP AV) and HomePlug GreenPHY (HP GP).

MoCA requires an already established coaxial system and possibly more than two coaxial plugs, which are limited in today's households.

Finally, Ethernet communication provides the highest reliability, but it can be costly. It is usually deployed in enterprise buildings with a sophisticated network structure. In residential environments, users often employ Ethernet for nonmobile applications, and its main disadvantage is the requirement for new wiring. Therefore, in comparison to MoCA and Ethernet, PLC is a more promising technology for hybrid networks in terms of cost, flexibility, and pervasiveness of connectivity possibilities.

1.3 Power Line Communication: Applications and Market

1.3.1 Easy, Low-Cost, High-Throughput Connectivity

Owing to the growing demand for reliability in home networks, wireless and power line communications are combined by several vendors to deliver high rates and broad coverage without blind spots. PLC is at the forefront of hybrid networking for residences, as it provides easy, plug-n-play, and high-data-rate connectivity. Its main advantages are its wider coverage compared to Wi-Fi, data rates up to 1.5 Gbps, and the fact that it does not require new wiring or infrastructure.

PLC can handle bandwidth-hungry applications thanks to its high data rates, but it can also be employed for home automation and low-rate networking. Smart appliances

(TV, refrigerator, lights, etc.) are inherently connected to the power grid, hence they can use the power line for both power supply and communications. This property of PLC proves very efficient for future connected homes, as they will use multiple smart appliances for comfort, security, and energy savings. Figure 1.3 presents examples of residential PLC applications.

Because of all the advantages discussed above, PLC is widely adopted in residential and enterprise networks. HomePlug, the leading alliance for PLC standardization and certification, estimates that more than 180 million PLC devices have already been shipped and that the expected annual growth is more than 31 percent over the next years. HomePlug also proposes different solutions for home automation and high-data-rate local networks. The most popular specification for high-data-rate PLC, employed by 95 percent of PLC devices, is HomePlug AV. This specification was adopted by the IEEE 1901 standard [5].

In this book, we focus on indoor and broadband PLC, in the frequency range of 1–80 MHz, and more specifically on the HomePlug AV and IEEE 1901 specifications. However, note that there also exist narrowband solutions for outdoor reliable communications with applications on power distribution automation, demand-response control, and meter-to-grid connectivity. These solutions are implemented in rural, urban, and suburban areas. The IEEE 1901.2 standard provides guidelines for narrowband PLC using frequencies below 500 kHz and data rates of up to 500 kbps [6].

1.3.2 PLC for Bandwidth-Hungry Applications

PLC has been very popular in home networking for extending Wi-Fi coverage and for providing connectivity to a wide range of applications. PLC vendors offer a wide range of devices supporting different data rates and Wi-Fi capabilities. In many residential environments, PLC solves Wi-Fi connectivity issues thanks to hybrid devices that provide multihop PLC/Wi-Fi connectivity to mobile users in different rooms and floors. Figure 1.3 shows examples of such hybrid devices. In general, PLC can have a much wider coverage – up to 300 m – than Wi-Fi. However, as we discuss in this book, performance largely depends on the power grid structure.

PLC is also being used as an additional medium for aggregating bandwidth along with Wi-Fi. Consumers of PLC devices usually connect PLC to TV, gaming consoles, whole-home audio, security cameras, and network storage. They exploit the abundant power outlets and electrical wire infrastructure in residential buildings. PLC promises Gbps rates, and hence can support 4K/HD streaming, file sharing, and other demanding multimedia applications.

PLC has been considered a reliable medium for in-vehicle communication (e.g., car, plane, train, and ship scenarios) [7]. For instance, PLC can exploit the existing power distribution infrastructure to deliver high-speed services to every cabin or to every seat in vehicles. Such applications are becoming popular, but their deployment requires further research.

Finally, PLC has use cases in enterprise environments too. Offering additional bandwidth, it can be used for fault tolerance, coverage extension, and smart offices. Recently,

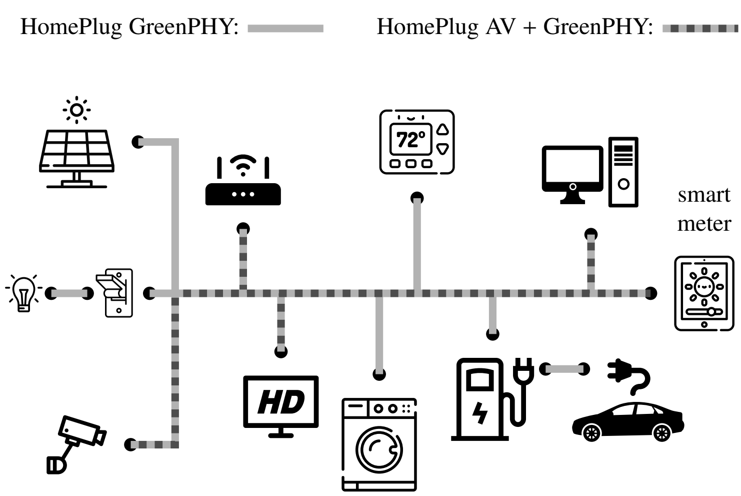

Figure 1.4 HomePlug GreenPHY examples.

PLC has been shown to efficiently work on data centers [8], for managing multiple servers and adding resilience to a system where communications could fail for multiple reasons.

1.3.3 PLC for Home Automation and IoT

PLC is an ideal networking candidate for smart appliances connected to the power grid. HomePlug alliance released the specification GreenPHY for applications that require low-power, low-rate, reliable networking. GreenPHY has been defined and developed in collaboration with the US Department of Energy, utility companies, and automobile manufacturers. One of the useful features of GreenPHY is the interoperability with high-bandwidth AV devices, hence potentially with the entire home network, without the need for special bridges to convert communications signals, as we show in Figure 1.4.

Multiple solutions use GreenPHY, ranging from home automation to vehicle charging. Smart appliances using GreenPHY, such as refrigerators, washers, heating, and air conditioning, contribute to an energy-efficient and connected home. GreenPHY is also integrated as a communication solution for electrical vehicle charging [9]. GreenPHY enables robust, low-power, and low-cost communications for all these applications.

HomePlug GreenPHY chipsets have more flexibility in deployment compared to AV. The chipsets can be integrated in many sensor systems and hardware platforms. For example, there are guidelines for integrating GreenPHY chipsets with Rasberry Pi [10]. This gives a wide range of possibilities and applications and enables users to create custom automation systems for residential or enterprise environments.

In addition to HomePlug GreenPHY, there are other popular communication protocols for home automation and smart metering over power lines. For instance, INSTEON uses the X10 technology developed in 1975 on 131.65 kHz channels [11, 12]. X10 is limited to specific commands (e.g., commands that switch on/off a device, switch all units off, turn all lights off), whereas GreenPHY enables generic low-rate communications. Similarly, Netricity, which is built on the IEEE 1901.2 standard, enables 500 kbps rates on frequencies below 500 kHz [13]. Applications of Netricity span over smart grid, distribution automation, and net metering demand and response.

1.4 Standardizations and Specifications

Broadband PLC specification started developing in the late 1990s, mainly supported by the HomePlug Powerline Alliance, Universal Powerline association (UPA), and High-Definition Power Line Communication (HD-PLC) alliance. The timeline of PLC specifications is shown in Table 1.2. The first specification, HomePlug 1.0, was released in 2001 and supported 14 Mbps capacity. The Telecommunications Industry Association (TIA) published the international standard TIA-1113 in 2008, which was based on HomePlug 1.0, released 7 years earlier. HomePlug AV is the successor of HomePlug 1.0, published in 2005. HomePlug AV substantially improves capacity upon earlier specifications, yielding up to 200 Mbps. Since its inception, HomePlug AV has led the PLC market with hundreds of millions of devices.

HD-PLC and HomePlug had developed different protocols for PLC. The existence of noninteroperable PLC devices initiated a standardization effort by both IEEE and ITU-T, in 2005 and 2006, respectively. The IEEE 1901 and ITU-T G.9960/61 standards for PLC were released in 2010, including coexistence protocols for diverse devices [14, 15]. Coexistence is enabled through the intersystem protocol (ISP) specified in IEEE 1901 and ITU-T G.9972, whose support is mandatory for IEEE 1901 devices [16].

IEEE 1901 defines the protocols and functions of PHY/MAC layers for high-speed power line communications. The standard specifies protocols for both in-home networking and access networking, in the frequency range 1.8–50 MHz. Access is defined as a communications system of high-speed data on frequencies above 2 MHz over medium- and low-voltage power lines that distribute electricity to end user premises, enabling a communication link between the power utility infrastructure and the residence or enterprise. The power lines can be outside or within a building. The IEEE 1901.2010 standard consolidated two existing specifications in the market: fast Fourier transform (FFT) orthogonal frequency-division multiplexing (OFDM) modulation from HomePlug and TIA-1113 technologies and wavelet OFDM modulation from HD-PLC technology. HomePlug AV and GreenPHY are interoperable with IEEE 1901. GreenPHY was introduced in 2010, mainly for reliable and low-rate communications, as it only uses the most robust modulation schemes of IEEE 1901. It has up to 75 percent lower power consumption compared to HomePlug AV. The amendment IEEE 1901a in 2019 defines a flexible way of separating wavelet OFDM channels for IoT networks.

IEEE has published the **IEEE 1901.2** standard for narrowband communication, which targets communication below 500 kHz and smart grid applications [6]. In 2018, IEEE also published **1901.1** standard for medium-frequency (less than 12 MHz) PLC

Table 1.2 PLC standardization timeline

	HomePlug	ITU-T	IEEE
2001	HomePlug 1.0 release		
2005	HomePlug AV release		IEEE 1901: project authorization
2006		ITU G.hn: project authorization	
2008	TIA-1113 release		IEEE 1901 technical proposal selection
2010	HomePlug GreenPHY release	G.9960, G.9961, G.9972 published	IEEE 1901 standard release
2011		G.9963 published	
2012	HomePlug AV2 release		
2013			IEEE 1901.2 and 1905.1 release
2014			IEEE 1905.1a amendment
2018			IEEE 1901.1 standard
2019			IEEE1901a amendment

and smart grid applications [17]. Finally, the **IEEE 1905.1** standard focuses on heterogeneous networks comprising Ethernet, PLC, Wi-Fi, and MoCA.

The **ITU-T G.hn** standard defines networking over power lines, phone lines, and coax cables with data rates up to 1 Gbps, unlike IEEE 1901, which is restricted to power lines. G.hn is a home network standard, as opposed to being just a PLC standard, and targets combinations of existing wiring in a typical home (such as phone, power, and coax cables) to deliver a unified network. G.9960/61 standards define the PHY and data link layers for communication, and G.9972 defines coexistence functions between G.hn and IEEE 1901 with ISP. Synchronization with ISP is achieved using a special OFDM signal of sixteen continuous symbols.[1]

After IEEE 1901 and ITU-T G.hn were published, new specifications were released for Gbps rates. For instance, HomePlug AV2 optimizes PHY and MAC layers for 1.5 Gbps throughput, while maintaining interoperability with IEEE 1901 and older HomePlug devices. Compared to older specifications, state-of-the-art standardizations reduce overhead in the MAC layer and introduce multiple antenna techniques (MIMO) by exploiting the existing two-wire electrical infrastructure for additional antennas. HomePlug AV2 and ITU-T G.9963 use MIMO transmissions on the PHY layer [18].

[1] A symbol is a waveform for a fixed period of time.