Chapter 4

Power Line Communication Technology Overview

4.1. Introduction

Ubiquitous networks in home environments are now expanding the connectivity to consumer electronic devices, that we term "things" or "objects", from which we build home network services. The connections can be thing-to-thing or thing-to-gateway to reach the servers in the network. These servers, launched by various utilities or service providers, can then store data for cross-referencing, compiling and optimizing services (electrical consumption, remote home health-care, home sensors, etc.). In order to make these ubiquitous networks available at home, various mediums and networking technologies are being developed at the physical, data link and network layers of the so-called open system interconnection or OSI model [COM 06].

Power line communication (also known as PLC) [PLC 09] has proved in the past years that it is a good candidate for these types of networks, with a mature, stable and secure level of technology. PLC is used in both high and low bit-rate applications giving IP or media access control (MAC) layer connectivity to the sensors, things or

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The Internet of Things: Connecting Objects to the Web Edited by Hakima Chaouchi

devices at home. This chapter aims to present the state-of-the-art PLC technology for home networks from the existing (low and high bit-rate) standards to the usages and integration in a complete "things connected" architecture.

4.2. Overview of existing PLC technologies and standards

In this section we present the various PLC technologies [PLC 09] that are used to transmit communication signals at high and low bit rates, on the electrical support of the so-called "indoor" or "in-home" environment, in other words, PLC technologies in any "private" electrical network as opposed to electrical networks using medium or high voltage and operated by electrical power providers. Private electricity networks are found in multiple environments, such as houses, apartments, residential buildings, service buildings (offices, hospitals, hotels, etc.), industrial buildings (factories, telephones, etc.) and other possible electrical networks (aircraft, vessels, cars, etc.).

In contrast to public electrical networks, "indoor" PLC networks are not subject to regulations and enable network engineers to set up communication networks using electrical cables as support. The great advantage of PLC technologies lies in the simplicity of their implementation, since they use existing electrical networks. It is unnecessary to install new cables for PLC networks, which permits great flexibility in deploying applications that require important data transfer, such as multimedia, or for uses that require little bandwidth, such as home automation. These technologies have grown significantly in recent years with the success of Internet access offerings, such as service combination packages (Internet, phone and TV) and the provision of "Internet boxes" by Internet service providers (ISPs). Internet boxes require "indoor" technologies to be connected to networks.

It seems that now PLC technologies have reached a sufficient degree of maturity to provide reliable equipment for domestic broadband use and home automation. There is still no standard for PLC technologies, but industry groups like the HomePlug Alliance have helped to develop standards between different products, promoting compatibility between equipment incorporating the same specifications. Moreover, these technologies can be used in addition to current home network standards, such as Digital Living Network Alliance (DLNA) and Universal Plug and Play (UPnP) [MIL 01] for connecting heterogenous devices through the private electrical network. Finally, as most home devices need electrical power, it is obvious that PLC technologies are well placed for creating a ubiquitous indoor object network, where any device could communicate and get power through the electrical network.

4.2.1. *History of PLC technologies*

PLC technologies are not new. The first known deployment was initiated in England in 1838 by Edward Davy, who proposed a solution to remotely measure the battery levels of sites through the electrical line between London and Liverpool. In 1897, he presented the first patent (British patent no. 24833) of a measurement technique to remotely measure an electrical meter over electrical cables.

Named ripple control, the first PLC systems were developed on medium and low voltage electrical networks in 1950. The carrier frequency was then between 100 Hz and 1 kHz. The purpose was to establish communications via mono-directional control using remote signals for ignition and extinction of public lighting or to change the rate. Since then, producers and distributors of electricity have used the power network in order to monitor and control it remotely at a low bit rate. The first industrial systems emerged in France in 1960 under the name Pulsadis.

After this the first PLC system using the so-called Cenelec (European Committee for Electrotechnical Standardization) band, ranging from 3 to 148.5 kHz, was introduced. The Pulsadis and Cenelec systems allowed two-way communications on low voltage electrical cables. Their applications range from reading electrical meters to home automation (intruder alarms, fire detection, detection of gas leaks, etc.). The powers injected were much smaller than their predecessors, since they were reduced to the order of milli-watts.

Recently, the advent of technologies for broadband access has fostered the development of PLC technologies to offer integrated services with a reliable and robust system at the physical and data link layer of the OSI model. Despite a lack of standardization for PLC products, industrial consortiums, such as the HomePlug Alliance, has helped to define standards for certain compatibility between PLC products. The full range of PLC equipment can therefore offer any kind of modern network service through the power systems. Today PLC technologies have reached a certain maturity, enabling them to directly compete against other network technologies. They are therefore well positioned to create a ubiquitous home network for any kind of communicating devices.

4.2.2. *Different types of in-home PLC technologies*

The main technique used to transport the PLC signal through electric media is to add a modulated signal of low amplitude to the low voltage electrical signal around a center carrier frequency. There are two types of "indoor" PLC technologies that provide different rates depending on the frequency bands used.

The PLC "low bit rate" technology uses the 3-148 kHz frequency band and is mainly used for applications requiring low data transfer (<50 Kbit/s), such as home automation and sensor networks. "Broadband" or "high speed" PLC technology uses the 1-30 MHz frequency band. They can provide data rates ranging from 1 to 200 Mbit/s, depending on the standards used. They are perfectly suited for network deployments requiring high bandwidth and high quality of service.

Unlike other communication media, such as Ethernet cables, coaxial, fiber optics, etc. data transmission is not the main function of the electric cable. Transport data must be added to the electricity cables to feed the electrical energy (200V/50 Hz in Europe and, 100V/60 Hz in the United States and Japan). Moreover, the electric cable is a shared media and is sensitive to radio noise. Thus, various PLC technologies have benefited from the technical maturity of modulation and coding. They have better control of access to physical media and provide a robust signal with respect to the electromagnetic noise environment. A set of mechanisms have been integrated at the physical and data link layer to improve data transmission and media access.

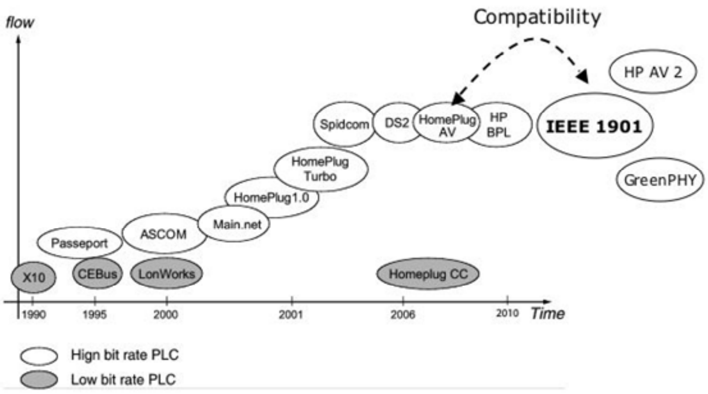

Figure 4.1. *Different generations of PLC technologies for a high and low bit-rate*

Figure 4.1 shows different generations of high and low bit-rate PLC technologies with the two categories (high bit-rate and low bit-rate) that will be described in the next sections.

4.2.2.1. *In-home high-speed/broadband PLC technologies (with high bit rate)*

PLC devices are now widely used and the high bit-rate ones are often bundled in ISP offers (such as the digital subscriber line, or DSL, providers in Europe or the Cable providers in the US) as the need for in-home bit rate and stability is becoming crucial for high definition video streaming services.

As electric cables are a shared media and are sensitive to radio noise, the data transmitted by PLC technologies may be subject to collisions or signal loss on the wire. Taking these constraints into account, the various broadband PLC technologies have integrated a set of mechanisms at the physical and data link layers to minimize the risk of collisions and ensure reliable data transport. These mechanisms provide adequate flow for deploying network applications requiring high bandwidth usage, such as voice over IP (VoIP), video streaming, file sharing, etc. The theoretical speeds proposed can be up to 200 Mbps for HomePlug AV (audio and visual) standard and 14 Mbps for HomePlug 1.0 standard. According to the PLC technology used, the signal is modulated in amplitude, frequency or phase around a carrier frequency.

To transmit a robust signal that is resistant to external disturbances, the different HomePlug standards use a modulation technique called OFDM (orthogonal frequency division multiplexing) at the physical layer. This technique allows the frequency band to be split into narrow strips, each carrying a portion of the binary information. The bands are independent from the frequency and do not interfere with each other.

To provide an optimum speed quality on each PLC link, the HomePlug technologies offer several different modes of modulation for OFDM symbols on each sub band. For example, the different modes can vary from binary phase-shift keying, or BPSK, coding 1 bit per symbol and per frequency, to 1024-QAM (quadrature amplitude modulation), coding 10 bits per symbol and frequency. Each HomePlug PLC station connected to the electrical network evaluates the transmission channel quality of the link to the other stations in order to optimize coding and modulation and use the best stations for current transmission quality.

This information is stored in a table, called a ToneMap, on each device. Moreover the OFDM technique allows some sub-bands to be deactivated in order to respect other RF technologies using the same sub-bands. This technique is called “notching” and can dynamically turn some sub-bands on and off, respecting RF technologies such as amateur radios and the up-coming very high bit-rate DSL.

Figure 4.2 illustrates the different modulation table values that are stored in the memory of every piece of PLC equipment on the network. These tables are used to select the best modulation to communicate with PLC pairs on the network according to the network evolution.

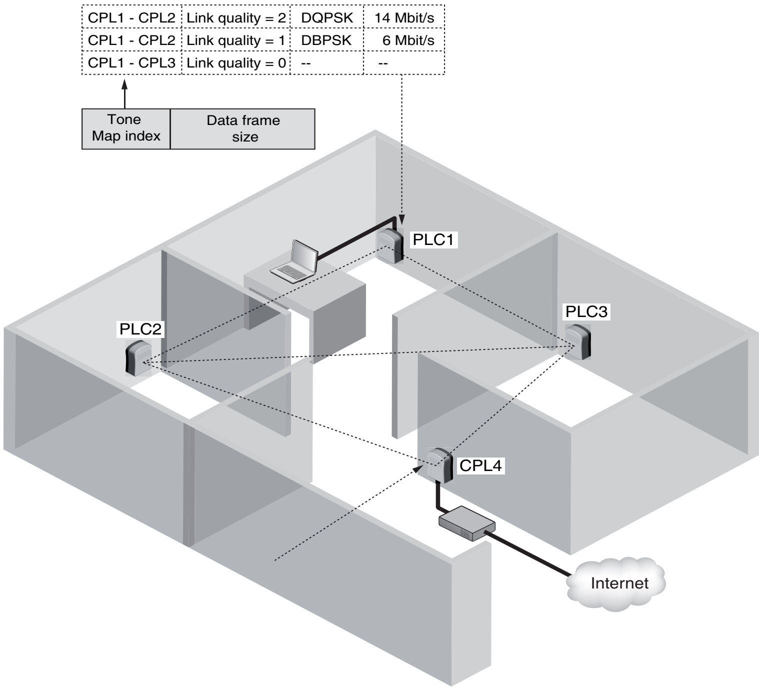

Figure 4.2. *Illustrations of the ToneMap stored on each PLC device*

In the HomePlug 1.0 specification, the frequency band is divided into 84 sub-bands, and HomePlug AV uses 917 sub-bands at the physical level. Figure 4.3 below illustrates this idea.

In the PLC systems, as for radio systems, transmission prevents the station listening and sending a stream simultaneously on the transmission frequency. As a result, the station cannot hear the collision. To reduce collisions between packets and improve media access, HomePlug 1.0 technologies use a method called CSMA/CA (carrier sense multiple access/collision avoidance). However, as the CSMA/CA algorithm does not guarantee a minimum transmission delay, the HomePlug AV standard proposes an allocation of timeslots, called TDMA (time division multiple access) for the transmission of data on media. This provides a better quality of service compared to HomePlug 1.0 technology, improving the level of guaranteed bandwidth, latency and jitter. In addition, these time slots are synchronized to the zero crossing of the electrical current, enabling deterministic synchronization of PLC equipment without a specific clock.

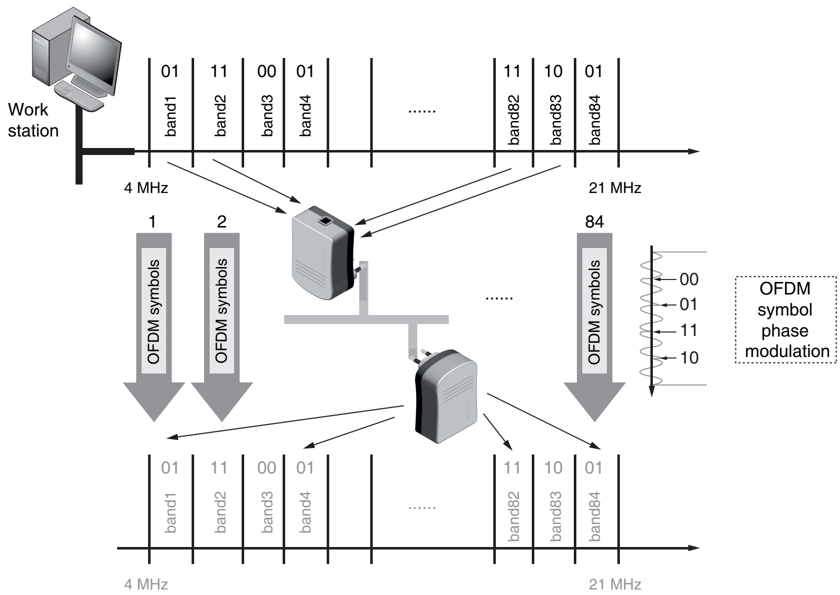

Figure 4.3. *Sub-bands usage in HomePlug 1.0*

HomePlug PLC technologies use a two-frame format, as shown in Figure 4.3. The long frame is composed of a delimiter start of frame, a section on data (Payload) and an end delimiter frame. Then, the short frame has a response delimiter used by the automatic repeat request process. Thus, the response frame transmitted by the receiving station can determine whether the data were received correctly by sending a positive acknowledgment to the originating station. However a negative acknowledgment is sent if the data were corrupted or incorrect and will result in data retransmission.

In the HomePlug AV standard, an additional response, selective acknowledgment, was added to compensate for the fact that PLC stations between two stations are not necessarily symmetrical in terms of data rate. If the frame goes beyond its maximum size (160 OFDM symbols for data in the HomePlug 1.0 standard), mechanisms of fragmentation and reassembly are implemented.

Furthermore, media access is controlled through a mechanism for accessing media between two frames called inter-frame spacing (IFS). IFS is different depending on transmission or reception. In addition to IFS, periods of containment and resolution of priority are used. Containment periods allow each station to calculate a random time, called the back-off time, which reduces the risk that stations transmit at the same time. To guarantee quality of service according to the priorities of each station, resolution priority periods (PRP1 and PRP2) are added to the waiting time. Figure 4.4 illustrates the frame exchange between two PLC stations at the data link layer. Information relating to priority access to the channel is indicated by higher layers using the headers defined in the virtual local area network (VLAN) IEEE 802.1Q, presented in Table 4.1.

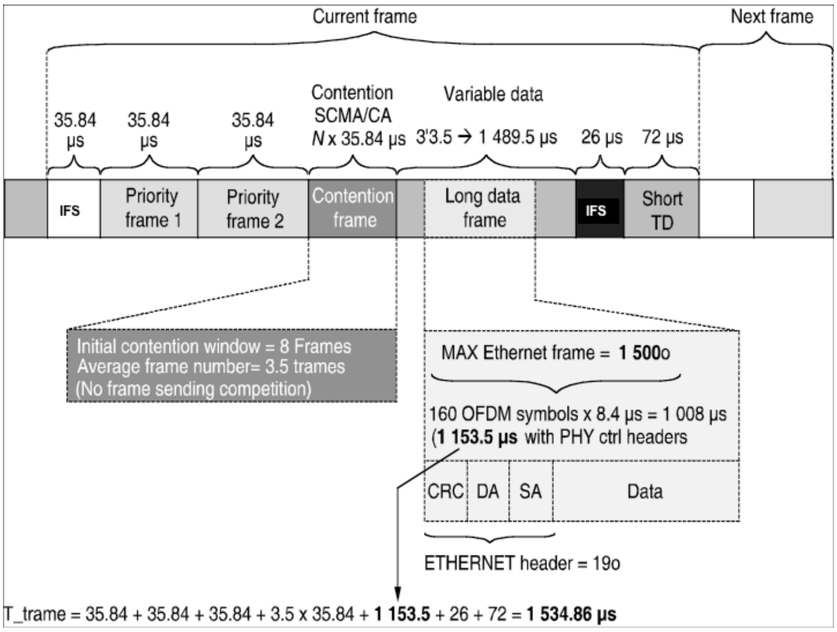

Figure 4.4. *Illustration of the frames exchanged between two PLC stations at the data link layer*

Priority	VLAN field value	Application class
Priority 3	7.6	VoIP (less than 10 ms transmission time)
Priority 2	4.5	VoIP (less than 100 ms transmission time)
Priority 1	2.3	Raw data transmissions
Priority 0	0.1	Limited data communications

Table 4.1. *Priorities in PLC devices based on the VLAN field*

Furthermore, the use of VLAN tags enables the creation of virtual networks at various levels of the OSI layers (PLC virtual networks, VLANs, MAC overlays, etc.). Thus, the VLAN tags can be used to implement a number of IP services for different levels of data traffic and applications, such as RSVP (ReSerVation Protocol), DiffServ for multimedia traffic, IEEE 802.1D, etc.

Finally, the HomePlug 1.0 and AV are seen at interfaces as Ethernet IEEE 802.3. This choice simplifies the integration of existing devices, since Ethernet is widely deployed. As these PLC standards can be seen as MAC encapsulation techniques, the various MAC frames transmission modes, whether unicast, multicast or broadcast, are permitted. In addition, many network protocols that are above the MAC layer of the OSI model, such as IP-level routing mechanism, IPv6 protocol, transmission control protocol (TCP)/user datagram protocol (UDP) transmission etc. can be added to PLC stations that conform with HomePlug 1.0 and AV standards.

4.2.2.2. *In-home PLC technologies with low bit rate*

The low-speed PLC technologies are mainly used for home service automation that requires little transfer of information. The frequency used is 1 – 175 kHz, which allows for data rates below 50 Kbit/s. The spectrum of home automation usage in indoor environments is wide. It stretches to applications such as automation appliances, from a control center to the interconnection of sensors and actuators that communicate through the electrical network. The home automation applications are expanding quickly to help make electrical appliances “smart” and provide supervision of real-time information on the

Internet. Figure 4.5 illustrates the usage of the spectrum frequency for the different categories of PLC technologies, namely:

– low bit rate: between 3 kHz and 148 kHz;

– high bit rate: between 1 MHz and 30 MHz.

For low bit rate technologies, HomePlug CC supports different regional structures such as the Federal Communications Commission in the US, Association of Radio Industries and Businesses for Japan and the European Committee for Electrotechnical Standardization (CENELEC) A and B for Europe. CENELEC A and B bands are respectively in the 20-80 kHz and 95-125 kHz frequency bands. The Federal Communications Commission band is 120-400 kHz for the HomePlug CC MAC layer.

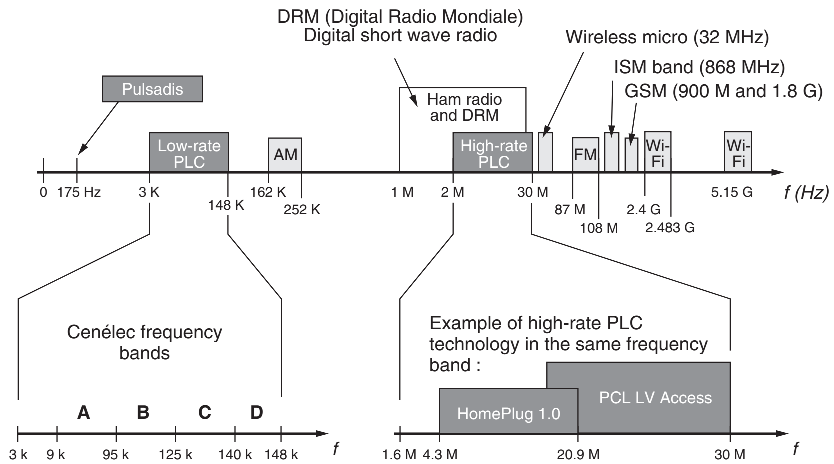

Figure 4.5. *Frequency spectrum for PLC technologies*

Low-speed PLC technologies are implementing data transfer and media access mechanisms that are less effective than broadband technologies because they tend to provide a minimum bandwidth. However, some protocols, such as X10 [ADA 01], HomePlug CC or PLCBUS, prove to be sufficient for use in home automation applied for home networks.

X10 is a PLC protocol developed in 1975. It is mainly dedicated to monitoring and controlling electronic modules connected to the electrical grid. The modules can be used for simple dimmers or more advanced sensors. The command signals sent by the transmitter modules generate a square wave signal that match the current signal. The transmission voltage is approximately 2.5 V, and the time of transmission is about 1 ms. In addition, X10 provides a certain level of redundancy to compensate for any data loss or distortion due to interference.

To ensure a better transfer rate, information is sent three times in a half-sinusoidal wave frequency of 120 kHz, each passing through zero current. The protocol frames are cut into two parts. The first is the client identifier, the second identifies the order. Each module has a customer ID code assigned to a "house" code of four bits. There are a total of 16 house codes, ranging from A to P, and each house code has 16 modules that can connect more than 256 different devices by assigning them a unique identifier. The "order" codes are set to five bits and can send orders to ignition or extinction, to increase and decrease the intensity or measure recovery values.

For security, X10 signals are stopped by the home circuit breaker that eliminates the issue of receiving instructions from neighboring apartments. However X10 encounters some problems with interference and slowness on the extended facilities. PLC-BUS is an improvement of X10 with better resistance to interference and can encode up to 64,000 different addresses. In addition to the standard dedicated command and control, the HomePlug Powerline Alliance (HomePlug CC) offers a low standard rate for home that remains compatible with other high-speed HomePlug devices.

HomePlug CC is derived from the draft proposal from the PLC chip company Yitran and implements a PHY/MAC layers close to the IEEE 802.15.4 MAC layer used for ZigBee. HomePlug is based on 127-byte MTU frames and a nodeID and networkID for addressing. Homeplug CC allows a co-existence with X10 by using carrier detection.

4.2.2.3. *Different network topologies*

The type of network can be defined based on PLC technology or on the topology of the electrical grid used, but also based on the management mode. There are three types of networks used by PLC technology:

– The master-slave mode is an illustration of the master and slave behavior of PLC technologies compared to the electrical grid master-slave topology.

– The peer-to-peer mode allows all PLC equipment in the network to play the same role at the same hierarchical level. These devices can exchange information with each other without being controlled by master equipment. This mode is widely used by the HomePlug 1.0 standard, as it allows us to quickly create networks.

– The centralized mode is a mixture of the two previous modes, where a piece of equipment is responsible for centralizing the management of networking and exchange between other PLC equipment. Other equipment may also swap information with each other without having to go through the centralized equipment. This equipment manages the allocation of media access to various PLC facilities that wish to communicate with each other. This mode of network is heavily used in HomePlug AV.

4.2.3. *Security*

As the electrical support is a shared medium, it can convey information outside of the home network, thus creating an opportunity to listen to communications or allow intrusion. Access to physical media is much more difficult than wireless technologies, however, because the electrical wire presents potentially dangerous security risks. To reduce attacks or eavesdropping on the PLC network, it is necessary to establish a security policy that takes data encryption, authentication and control equipment integrity of data into account. To increase network security, HomePlug standard allows us to create private networks based on PLC encryption keys for PLC equipment that is allowed in this network.

For example, in the HomePlug 1.0 standard there are two encryption keys, NEK (network encryption key) and DEK (default encryption key). The NEK key is encoded with the 56-bit data encryption standard algorithm derived from a password entered by the user and that can vary from four to 24 characters. This key will encrypt the data exchanged on the network and authenticate it between various pieces of PLC equipment. In order to enable secure data exchange between PLC network devices that belong to the same local area network, a shared NEK (network encryption key) is used on each piece of equipment. In order to configure the NEK on all remote pieces of PLC equipment that are connected to the electrical grid, each PLC station can use the DEK (default encryption key) that allow us to distribute the configuration information, such as login and password, in a secure manner. Moreover, the use of these keys can train several networks on a single PLC wiring, as shown in Figure 4.6.

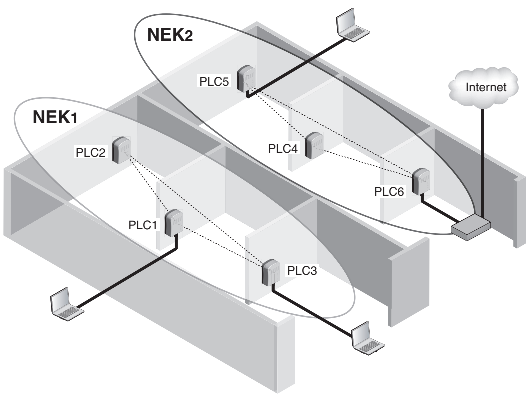

Figure 4.6. *Logical PLC networks*

4.2.4. *Performances of PLC technologies*

As indicated in the previous section, each PLC link can be subject to various constraints, such as weakening due to interference, multi-paths on the cables or the effects between cables to crosstalk. These constraints have the effect of reducing and mitigating the signal, which no longer allows the PLC to issue bonded information correctly. For example, the minimum attenuation of all meter/circuit breakers is 30 dB for a device emitting a signal at a frequency above 20 MHz. We consider a PLC signal at high frequency to be attenuated on average by half of its value when it goes beyond 100 m. To improve performance due to attenuation, a PLC coupler can be used to reduce the attenuation by 10 to 15 dB at certain frequencies.

In addition to electromagnetic interference, a PLC network is subjected to constraints related to the technology itself. The advertised rates do not correspond to those expected. For example, HomePlug AV devices offer a theoretical throughput of 10 to 200 Mbit/s data rate for a respective 5 to 60 Mbit/s. This difference is explained mainly by the size of the headers of frames used in HomePlug, and by the number of mechanisms used for reliable transmission in an electrical environment. Some of the data are transmitted to the control and management mechanism of transmission and only a fraction of the flow emitted by the equipment matches the data transport themselves.

Moreover, when the number of stations increases, throughput decreases with the additional latency added by contention periods or of priority periods. When the network consists of several stations, we can estimate the throughput capacity of each station as being almost equal to the maximum useful throughput divided by the number of stations in the network.

Despite these limitations, PLC technologies are well suited to applications requiring high speed, such as VoIP, audio and video streaming, etc. Additionally, these technologies are very competitive with regards to competing technologies, such as WiFi or Ethernet. Table 4.2 summarizes the various technologies with regard to their theoretical and practical throughput.

Layer 2 technology	**Max theoretical throughput (Mbit/s)**	**Max real throughput (Mbit/s)**
Ethernet 10M	10	8.08
Ethernet 100M	100	90.06
HomePlug 1.0	14	5.1
HomePlug Turbo	85	40
HomePlug AV	200	150

Table 4.2. *Summary of the different PLC technologies*

Table 4.3 presents the low and high bit-rate technologies and their main characteristics.

PLC family	Technology	Characteristics (throughput, PHY, indoor/outdoor)	Vendors
Low bit rate	X10	Throughput < 1 Kbits/s	PowerHouse Thomson
	HomePlug CC	Throughput < 50 Kbits/s Indoor and outdoor Specific MAC layer	Yitran, Renesas, Ariane Controls
	Echelon	Throughput < 10 Kbits/s Outdoor only	Renesas
High bit rate	HomePlug AV	Throughput 200 Mbit/s at PHY Max TCP throughput 60 Mbits/s Commonly used for in-home applications	Intellon, Devolo, Motorola, Linksys
	UPA	Throughput 200 Mbit/s at PHY MAX TCP throughput 60 Mbits/s Outdoor usage	DS2, Corinex, Netgear
	CEPCA	Throughput 220 Mbit/s at PHY MAX TCP throughput 70 Mbit/s In-home usage in Japan	Panasonic

Table 4.3. *Maximum throughput for different technologies*

4.2.5. *Standards and normalization*

PLC technologies emit radio waves in certain frequency bands and are susceptible to interference. Many standardization bodies, telecommunication and electrical engineering standards have established rules governing the limits of disturbance allowed in order to optimize the transmission channel and signal processing techniques to be implemented. Among the organizations working on electrical standards are Cenelec and the International Electrotechnical Commission. The European Telecommunication

Standards Institute is formulating standards in telecommunications. As part of the electromagnetic immunity, PLC equipment must meet electromagnetic compatibility and low voltage requirements. In addition to the above organizations and institutions, some associations and consortia play a role in PLC "pre-standardization" or standardization.

For PLC technology and standards in the in-door environment, there are three main families of technologies, as shown in Table 4.4 below.

Technologies or standards	**Industrial consortium**	**Technologies**
HOMEPLUG	Consortium HOMEPLUG (US) Leader: INTELLON	HomePlug 1.0, Turbo (throughput of 14 and 85 M) HomePlug AV (throughput 200 M) Technology: OFDM, CSMA/CA
UPA	Consortium UPA (EU) Leader: DS2	UPA (throughput 45 M) UPA HD (throughput 200 M) Technology: OFDM, CSMA/CA
CEPCA	Consortium CEPCA (Japan) Leader: PANASONIC	HD-PLC (throughput 220 M) Technology: wavelets, TDMA
IEEE	IEEE P1901 WG	Draft standard based on HomePlug AV

Table 4.4. *Standardization bodies for the high bit-rate PLC technologies*

As shown in Table 4.4, recent years have seen the development of several PLC technologies (HomePlug, UPA and CEPCA), with the emergence of a standard market given the equipment currently deployed around the world. For example, with HomePlug, more than 20 million products had been sold by the end of 2009. These three technologies are not interoperable and have become important for the PLC market to establish an international standard, which should be independent of a particular industry consortium.

In order to manage the co-existence of PLC technologies, the CEPCA alliance has developed a technical proposal based on a commonly distributed coordination function that allows us to manage time and frequency spaces between different technologies. This allocation is based on the following elements:

– management of hybrid access between frequency division multiple access and TDMA;

– management of quality of service through a system based on TDMA time slots, as in HomePlug AV for high definition video applications.

These two principles should avoid mutual interference and maximize the use of the media communication network.

A working group in the US standardization body IEEE, which has established the major networks and telecommunications standard currently used as Wi-Fi (based on the IEEE 802.11 standard), is working on the implementation of an IEEE standard for PLC technologies called IEEE 1901. The IEEE 1901 standard is based on the draft standard *HomePlug-Panasonic-HiSilicon In-Home* proposed jointly by the HomePlug consortium and CEPCA Alliance. IEEE 1901 standard is interoperable with HomePlug AV equipment already deployed in the market as it incorporates the specifications of the HomePlug AV standard. However, the HomePlug AV standard is not compatible with HomePlug 1.0 but it offers several mechanisms of coexistence between these technologies that are either mandatory or optional. In section 4.2, we propose the existing interconnection mechanism for PLC technologies is analyzed and we suggest some solutions for bringing together different technologies to connect objects in the home environment.

4.3. Architectures for home network applications

The increasing demand of home automation by many households in the world has led to the creation of new home services, such as VOIP, data sharing multimedia (images, video), telecare for the elderly, security systems, sensors and actuators for home automation, etc. In this context, PLC technologies are well situated for deploying ubiquitous home networks. Their major advantage is the ability to provide a large panel of network facilities by simply using the electrical grid.

In this section, we present different types of PLC architecture for deploying home network applications spanning from high bit rate to low bit rate technologies. We also describe how PLC technologies can be interconnected to form a complex home network environment.

4.3.1. *Architecture for a high bit-rate home network application*

Today, the emergence of high-speed network access at the home has provided end users with high quality bandwidth and services. Most of these services rely on Internet access provided by ISPs through modems or more complex Internet boxes. Currently, the diversity of PLC-related technologies can meet these expectations. Indeed, current PLC technologies offer data rates that are sufficient to deploy broadband services using the existing electrical media. Thus, the simple connection of PLC enclosures through a socket allows the power grid to create robust and secure communications networks. For example, these technologies (HomePlug 1.0, HomePlug AV, etc.) allow the broadcast of audio and video content, or provide the ability to share an Internet connection with an optimum quality of service. As presented in Figure 4.7, a typical architecture for this kind of high bandwidth application relies on the connection of a DSL modem (Internet box) with a PLC interface to an electrical plug. Thus, the DSL modem access is extended to the home electrical grid that serves as the backbone of home Internet access and any electrical plug can be used to get access to the services that the box is delivering. Wireless interfaces that are embedded with PLC devices are available today. Thus the electrical grid can serve to extend the Internet connectivity with wireless access points by a simple connection to any electrical plug in the home. It is interesting to note that such PLC-WiFi devices benefit from getting energy and Internet connectivity within a single cable that can leverage their deployment in an in-door installation.

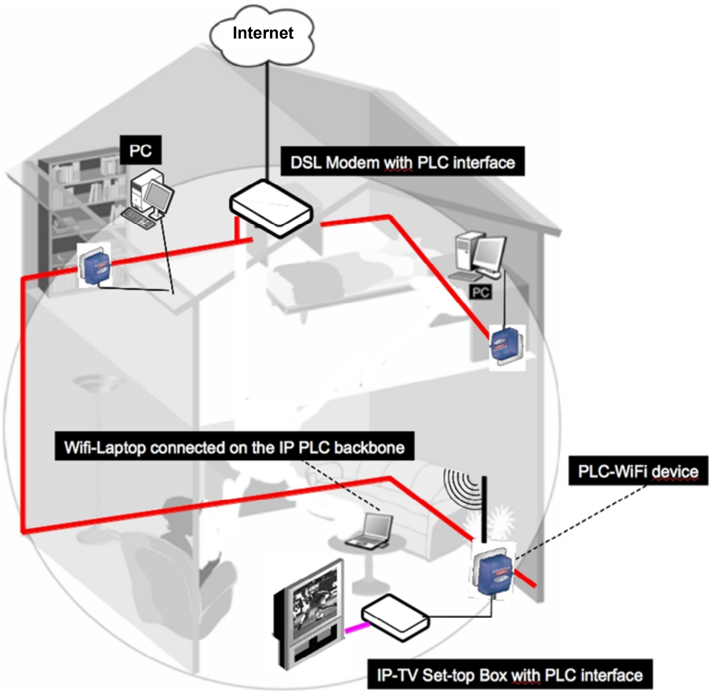

Figure 4.7. *Architecture of the scenario 1 using high-bit rate PLC devices*

Our example in Figure 4.7 depicts such scenario where an IP-TV set-top box, a PLC-WiFi device and several computers have access to high bandwidth services through PLC devices.

Besides of the above described architecture, high-speed PLC technologies can be deployed with no Internet connectivity to deliver services for an internal usage. Thus the home electrical grid can serve as a transmission channel for various applications as multimedia file sharing, internal telecommunication system, real-time video streaming, etc. Figure 4.8 depicts this sort of usage where a server and a network attached storage equipment are connected to the home electrical grid via a PLC device and provides access to different multimedia content simultaneously to a PC client that is connected to the home electrical grid through a PLC device.

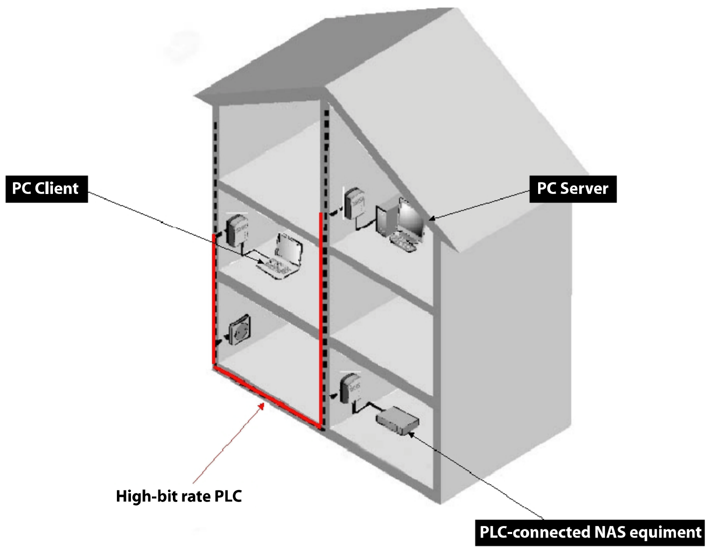

Figure 4.8. *Typical high bit-rate PLC architecture in the home*

Despite the ease of deployment offered by PLC technologies in the home environment, some critical factors concerning their performance and security have to be taken into account. First, as stated in section 4.2, the bandwidth delivered through PLC technologies decreases with length of the signal propagation and of number of PLC devices that are connected to the electrical grid. Thus, it is important to design the PLC infrastructure with regards to these factors by adding PLC signal repeaters.

Moreover, as PLC signals can bypass electric meters of an individual installation, it is important to protect the PLC networks deployed with the security mechanisms described in section 2.3. Adding signal filters to the electrical meter is also a good solution for stopping PLC signals from private installations.

4.3.2. *Architecture for low bit-rate home network application*

In the context of the home network environment, low bit-rate PLC technologies are mostly used for home automation applications that require a low level of data transfer. These applications rely on the deployment of various sets of sensors (smoke detectors, infrared or video motion detectors, etc.), actuators (electrical switch, electrical motors, lighting systems, etc.) and controllers (software or hardware programmable devices, remote managing monitors, etc.) that can communicate with each other through the home electrical grid.

We can cite several common usages for home automation, such as lighting control, appliance monitoring, home security diagnostics, automatic watering systems, smart grids, intrusion detection, energy management, personal health services, etc.

Since the early deployment of home automation after World War I, these systems have radically shifted in the late 70s with the advent of the X10 specification. Today, PLC-based home automation technologies have reached a mature state and a large number of solutions and technologies are available in the market, such as X10, PLC BUS, 1-Wire, INSTEON, etc. As most of these technologies are not compatible with each other, in section 4.2 we present several interconnection solutions could solve this issue.

Home automation solutions with low bit-rate PLC technologies can be deployed based on three different architectures that we will present below.

Centralized architecture is based on a central controller that has the dual role of collecting the information coming from various sensors and of sending trigger signals to actuators. Users have the opportunity to program the controller to perform a specific action based on the sensor information processed. This architecture is the most common and cheapest one as it only relies on one central controller that can manage a wide range of sensors and actuators.

Distributed architecture allows each module that is sensor or actuator to receive, send and manage information among all modules that are connected to the same electrical grid. Hence, modules have to embed sophisticated systems to achieve their role and are generally more expensive than regular sensors or actuators.

Mixed architecture is a combination of centralized and distributed architecture. This architecture is more flexible than the others as additional modules can be integrated easily in an existing home automation deployment.

In order to illustrate low bit-rate home automation deployments, we present a scenario based on centralized architecture in Figure 4.9. In this scenario, a smoke detector and a video motion detector are connected to the home electrical grid through PLC devices. These sensors send their information to a central controller that processes the incoming information and sends a signal to an actuator if a fire or an intrusion in the home is detected. The actuator is a simple speaker that produces different sounds depending on the event detected.

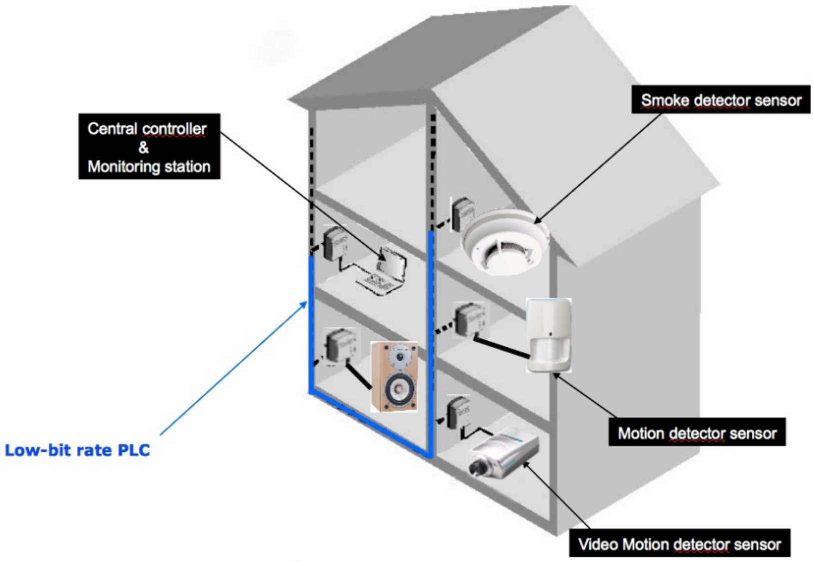

Figure 4.9. *Typical architecture with low bit-rate PLC technology for in-home applications*

The scenario presented before can be extended with a modem to offer remote access to the home automation deployment. This feature is commonly used for providing remote services for home security, personal health assistance, home installation monitoring, etc. Figure

4.10 depicts this kind of installation applied for a home security service. The home automation deployment is based on centralized architecture where a smoke detector and a motion detector send their information to a controller, which also serves to monitor the installation. A 56 K modem is connected to the controller via the home electrical grid and communicates its data flow to a remote operator via the local public switched telephone network. Thus, the remote operator can be alerted of different events and can react accordingly.

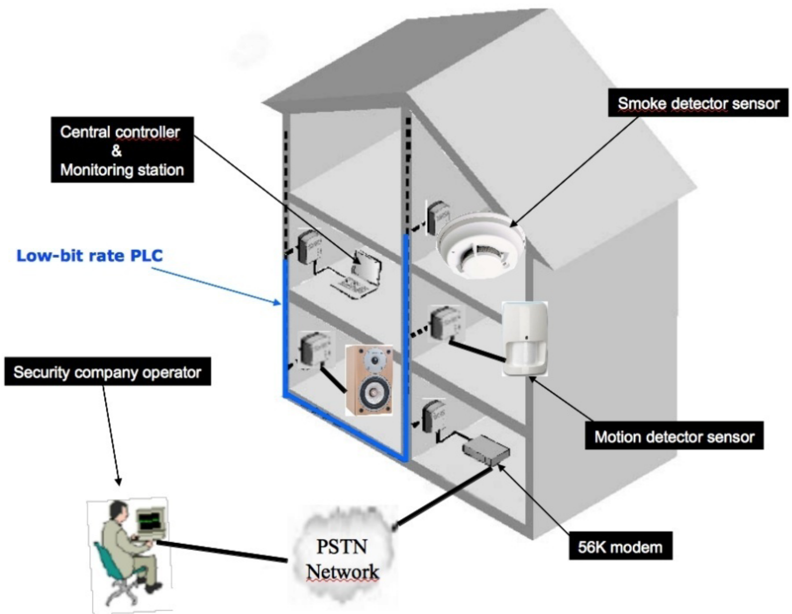

Figure 4.10. *Example of applications of low bit-rate PLC technologies*

4.4. Internet of things using PLC technology

Today many different systems must communicate in the house; computer systems, telecommunications, electronics, home automation, everything merges into a world called "digital convergence". The concept of digital convergence is related to the digital home and is evolving as an essential service provided to users by ISPs and industry. Access to mobility through the deployment of wireless technologies and the development of chips radio frequency identification (RFID) will soon allow the creation of an “Internet of Things” (IoT) to accompany users in each of their domestic activities. PLC technologies are well situated to serve as a ubiquitous network for deploying the IoT service in the home, as any object could use an electrical plug to communicate.

4.4.1. *Connecting objects in the indoor environment*

Recently, we have seen the emergence of objects with embedded communicating facilities, allowing them to either communicate through an Internet connection, or to share information via various existing technologies (X10, IEEE 802.15.4, IEEE 802.11, etc.) and protocols (IPv4, IPv6, etc.). Moreover the wide adoption of RFID standards has brought up new usage scenarios as an increasing number objects will be tagged and thus be identified. In the context of the home network environment, the family of communicating objects that we envision is very large; for example we can cite communicating objects, such as home appliances (refrigerators, oven, vacuum cleaner, etc.), consumables (bottles, food packaging, etc.), furniture (digital frames, cupboards, etc.), robots (cooking robots, cleaning robots, etc.), and so on. The list of objects that could communicate seems to be infinite as their usages. As stated earlier, PLC technologies are providing an ideal network solution for the home environment and are well situated for the deployment of communicating objects in the home. Such deployments could maximize home comfort applications with wider home automation offerings, which would enforce the emergence of a smart home solution [HAR 03]. Thus below we present some possible scenarios and architectures to handle the connection of objects in the indoor environment.

The first scenario that we propose is the things-to-things scenario for which any object can communicate with other object through the electrical grid of a house. The underlying architecture should be close to the person-to-person architecture described in section 4.2 where any connected device is in charge of communication management. In addition, this scenario should be used with the interconnection mechanism that we presented in section 4.2 in order to facilitate the interaction of a wide range of heterogenous objects with different embedded communication protocols.

In Figure 4.11, we present an example of a things-to-things scenario, where all objects can communicate with each other via the home electrical grid. In this example, a refrigerator maintains an inventory of products consumed and a cupboard lists the remaining products that are currently stored thanks to RFID tags and smart shelves. Then this information is transmitted to a computer that provides different statistical information about the food consumption and products' storage status. A user can also see the information of his or her food consumption that is displayed on the home television.

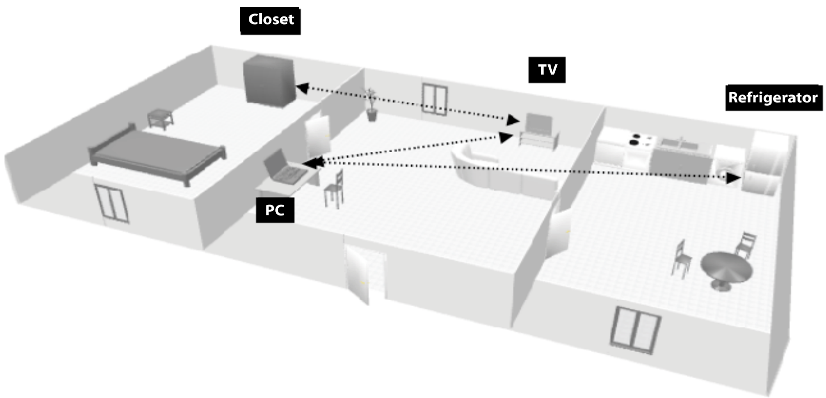

Figure 4.11. *Example of a things-to-things scenario in the home environment*

Traditionally, broadband modems (cable modems and DSL modems) have only enabled the connection of a single PC to the Internet via its USB or Ethernet interface. Operators have expanded their offers with triple service connection (Internet, TV and telephony) and the broadband modem has evolved into a new generation of modems with multiple Ethernet interfaces or with a wireless-enabled modem/router. To this extent, the home gateway initiative [HGI 06] has promoted solutions and use cases centered on a "home gateway" that will be the central communicating element of the house. Thus, we also propose another scenario that we call the things-to-gateway scenario. In this scenario the gateway could be a smart Internet box that would let objects communicate with external objects or with remote services (web servers, ONS [ONS 08], 3G phones, etc.). The gateway would also be in charge of managing, controlling, and authenticating the objects deployed in the home.

Figure 4.12 presents a things-to-gateway scenario where a refrigerator maintains an inventory of products consumed and lists the remaining products thanks to RFID tags. When the refrigerator becomes empty, it contacts the home manager server and retrieves the shopping list based on user instruction. Then an order can be generated and sent to a web-based shopping center to deliver the desired products at a defined time. The home manager server can also retrieve information about the number of products stored in the cupboard thanks to RFID tags and it sends this information to the home television.

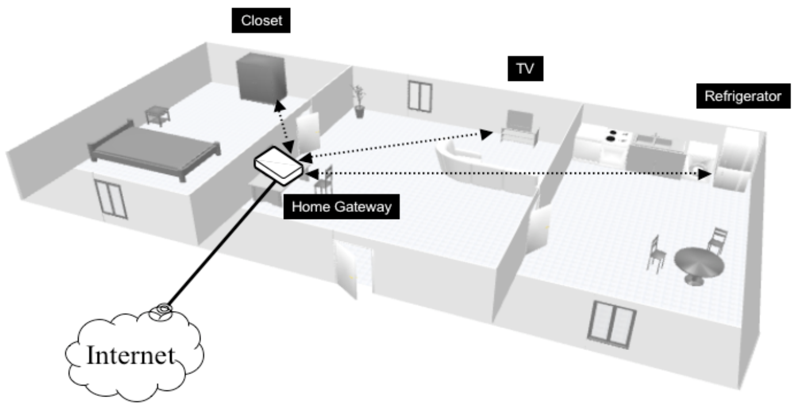

Figure 4.12. *Example of a things-to-gateway scenario in the home environment*

Here we have presented two different scenarios that use PLC technologies to connect objects in the home environment. These scenarios follow the ongoing efforts to establish an ambient intelligence [LES 99, REM 05] or smart home [HAR 03]. As an increasing number communicating objects will be available in the home environment soon, these scenarios have shown that PLC technologies are well situated to support the deployment of object networks in the home environment.

4.4.2. *Interoperability of connecting objects in the home environment*

One of the biggest problems of new technologies is the interconnection of different materials or technologies that are not designed to be compatible. This is the case when connecting between different types of PLC technologies or different communicating objects that belong to different constructors. To embrace these challenges, the Digital Living Network Alliance Consortium was created in the US. At present, it brings together around 200 members including leading companies involved in production of electronics, mobile devices and personal computers. Its purpose is to promote common standards and interoperability between products from different companies to create a network of electronic devices in the home. Although the standard is still in a development stage, Digital Living Network Alliance certification is already available.

Another example of interoperability effort is the Universal Plug and Play (UPnP) [MIL 01] which is a network protocol compatible with TCP/IP and UDP. It proposes is to foster communication between any number of devices on the local area network. UPnP uses an open architecture, allowing independence *vis-à-vis* of the media used. An UPnP service works by including a list of actions that the service responds to and then produces a list of variables that characterize the service performance. Each device can dynamically join a network, obtain an IP address, announce its name, specify its options on request and query other devices on their presence and capabilities. Thus, the interconnection of different communicating objects that respect the UPnP protocol can easily be achieved in the home environment using PLC technologies.

Coexistence between different network technologies, whether wired or wireless, can create critical disturbance. For example, propagation of the PLC signal on power cables creates an electromagnetic field that can disrupt not only the other communication systems, such as radio networks, but also the various PLC technologies themselves. However, cohabitation between PLC and wired technologies (Ethernet cable, fiber optics, cable TV, telephone cable, etc.) does not generate disturbance since the frequency bands used by these technologies are all located outside the frequency used by PLC technologies.

As presented earlier, high and low bit-rate PLC technologies can be deployed independently in the home environment. However, merging these technologies in a single deployment architecture should allow users to benefit from a wider range of facilities and usage. For example, it should be possible to allow deployment of a low bit-rate sensor network that could interact with content servers on a high bit-rate network. There is no cohabitation problem between low and high bit-rate PLC technologies because they transmit on two different frequency bands. Technology devices cannot, however, communicate with each other. Thus, using devices that are conform to Digital Living Network Alliance or UPnP protocol should allow this kind of cross-PLC technology deployment.

The coexistence of PLC and wireless technology is also possible, since the frequency bands used are different. The high bit-rate PLC technologies operate in the band 1 to 30 MHz and various IEEE 802.11 standards in those of 2.4 and 5 GHz. Moreover, some hybrids PLC/WiFi equipment is already available in the market, such as the NetPlug Turbo Thesys equipment that provides an electrical outlet with an Ethernet interface and an antenna for IEEE 802.11. Thus it is possible to deploy a hybrid network that employs any high bit-rate PLC technologies to create an Ethernet backbone through the home electrical grid (where each electrical outlet can be used with hybrid PLC/WiFi equipment to provide wireless connectivity). Furthermore, this hybrid deployment can provide an optimum performance and coverage to different communicating objects in the home.

Future applications will use both IPv4 and IPv6 network-layer protocols on both low and high bit-rate technologies. For instance, some light IP stacks have been developed to support low bit-rate applications, such as 6lowPAN [RFC 07a, RFC 07a] that implements a light IPv6 stack over IEEE 802.15.4 [CAL 02] data-link layer.

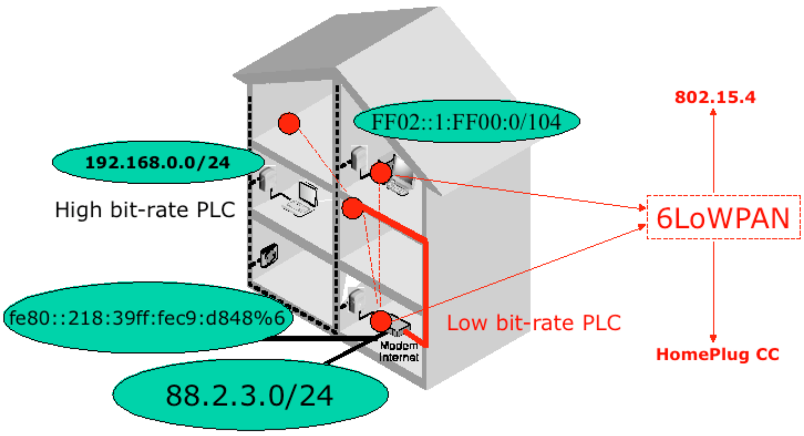

Figure 4.13. *Example of IPv4 and IPv6 cohabitation for home networking applications*

Figure 4.13 presents an example of a hybrid home networking application with an IPv4 and IPv6 configuration on the same network.

Since PLC technologies are widely used for in-home usage, we want to address some critical challenges for its adoption by the future IoT deployment in the home environment:

– *Heterogenity*: Bringing heterogenous technologies together or allowing different devices to communicate is a key feature, as future IoT deployment should be technology agnostic.

– *IPV6*: The upcoming adoption of the IPv6 protocol should be taken into account with any kind of communications support.

– *Scalability*: New solutions should be envisaged to scale the home networks to support the fast growth of connected devices.

– *Security*: Better authentication protocols and secure encrypted connectivity should aim to avoid unwanted intrusion or attacks.

– *Services*: The next generation of services should require a more functional device, such as a “home gateway” that should be secure and simple to use.

4.5. Conclusion

In this chapter, we have described the different PLC technologies and the current standards. We have detailed the different possible usage of PLC technologies in the IoT architecture. In 2009, the high bit-rate PLC technologies were commonly used for local Ethernet links in-home. With the combined service offers from certain ISPs worldwide, this technology will step forward common usage in low bit-rate applications (sensors networks, motion detection, smart metering, smart electrical in-home plugs, etc.).

Moreover, we have seen that PLC technologies can serve as a ubiquitous home backbone to support various other technologies, such as IEEE 802.11, IEEE 802.15.4, infrared, etc. Thus any electrical plug can serve as a communicating channel for any objects needing to communicate. With the development of home-networking technologies, we will see an increasing number of devices connected in-home and the PLC technologies are well situated to implement this future IoT in the home environment. The future challenge of enhancing heterogenity and interoperability mechanism among PLC technologies will certainly play a role in their adoption in the home environment.

Finally, as most of electronic devices need to be connected to a power supply, the home electrical grid can have a dual role; providing energy and network connectivity at the same time. This feature should also mean that PLC technologies become an incontrovertible candidate for the future IoT deployment in the home environment.

4.6. Bibliography

[ADA 01] ADAIR M., *Easy X10 Projects for Creating a Smart Home*, Technica Pacifica, 2005.

[CAL 02] CALLAWAY E., GORDAY P., HESTER L., GUTIERREZ J.A., NAEVE M., HEILE B., BAHL V., “Home networking with IEEE 802.15.4: a developing standard for low-rate wireless area networks”, *IEEE Communication Magazine*, vol. 40, p. 70-77, 2002.

[COM 06] COMER D.E., *Internetworking With TCP/IP Volume 1: Principles Protocols, and Architecture (5th edition)*, Pearson Prentice Hall, 2006.

[COO 03] COOK D., YOUNGBLOOD M., HEIERMAN E., GOPALRATNAM K., RAO S., LITVIN A., KHAWAJA F., *MavHome: An Agent-Based Smart Home*, Pervasive Computing and Communications (PerCom 2003), p. 521-524, 2003.

[HAR 03] HARPER R., *Inside the Smart Home*, Springer, 2003.

[HGI 06] HOME GATEWAY INITIATIVE, *Home Gateway Technical Requirements: Release 1*, HGI, 2006. (Available at: http://www.homegatewayinitiative.org/, accessed February 22, 2010.)

[LES 99] LESSER V., ATIGHETCHI M., BENYO B., HORLING B., RAJA A., VINCENT R., WAGNER T., PING X., ZHANG S. X., “The intelligent home testbed”, *Proceedings of the Autonomy Control Software Workshop*, 1999.

[MIL 01] MILLER B.A., NIXON T., WOOD C., “Home networking with universal plug and Play”, *IEEE Communications Magazine*, vol. 39, pp. 104-109, 2001.

[ONS 08] GS1, EPCGLOBAL OBJECT NAME SERVICE (ONS), 2008. (Available at: http://www.epcglobalinc.org, accessed February 22, 2010.)

[PLC 09] CARCELLE X., *Powerline Communications in Practice*, ArtechHouse, 2009.

[RFC 07a] KUSHALNAGAR N., MONTENEGRO G., SCHUMACHER C., *IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs): Overview, Assumptions, Problem Statement, and Goals*, Internet Engineering Task Force, 2007.

[RFC 07b] MONTENEGRO G., KUSHALNAGAR N., HUI J., CULLER D., *Transmission of IPv6 Packets over IEEE 802.15.4 Networks*, Internet Engineering Task Force, September 2007.

[REM 05] REMAGNINO P., FORESTI G.L., “Ambient intelligence: a new multidisciplinary paradigm”, *IEEE Transaction on Systems, Man and Cybernetics, Part A: Systems and Humans*, vol. 35, no.1, pp. 1-6, 2005.