POWERLINE COMMUNICATIONS SYSTEMS: OVERVIEW AND ANALYSIS

by

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ABSTRACT OF THE THESIS

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The electric power distribution grid is a medium over which fast and reliable communication services can be provided. Power Line Communications (PLC) systems provide an alternative to wireless communications in the transmission of data within buildings and vehicles. In recent years, increased interest in PLC systems for both commercial and residence applications has resulted in the development of standards for use of the electric power grid as a communications channel conveying messages in addition to power. The types of applications range from simple inexpensive services centered around networked household appliances, where data rates are on the order of kilobits per second, to Internet access via the electrical outlet wall socket, where data rates are on the order of megabits per second. Currently, PLC systems can accommodate high-

speed networking that includes broadband Internet access, voice over-IP, and the interconnectivity of home entertainment devices.

The development of a Power Line Communications system presents a significant challenge for the communications engineer due to the unusual channel characteristics that affect high-speed signal transmission. The electric power grid is designed for, and operated at, 50/60 Hz throughout the world. Furthermore, the topology of a local electric power grid network is often very irregular resulting in significant dispersion of the transmitted message signals.

This thesis presents an overview of the major features and characteristics of PLC systems, the fundamental properties of powerline channels, and an analysis of PLC system performance in the presence of realistic powerline channel conditions.

The development of a powerline communication system requires detailed knowledge of the electric power grid channel properties, such as the frequency transfer function and the interference processes, in order to choose a suitable transmission method. The noise interference and channel multipath effects are the main impairments to the performance of PLC systems. This thesis presents appropriate channel models for use in the design of PLC systems. In particular, the Bit Error Rate (BER) performance of a single-carrier Binary Phase Shift Keying (BPSK) system operating over a multipath channel is analyzed and compared with the performance obtained with a multi-carrier data transmission scheme.

Acknowledgements

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1. Introduction

1.1 Powerline Communications: An introduction

Currently in age of Information Technology, the present focus is both on creation as well as dissemination of information. In order to be able to reach the end users of information, the popular technologies currently being used include telephone wires, Ethernet cabling, fiber optic cabling, as well as wireless and satellite technologies. However, each of these information transmission techniques has its limitations involving cost and availability to reach the maximum number of users. Over the past few years, the increasing ubiquity of the Internet is creating a rapidly growing demand for larger bandwidth to the home and office. This search for new ways of transferring information has introduced Powerline Carrier (PLC) Communications, or more recently Broadband over Powerline (BPL), systems as an innovative format to exchange information. BPL systems use existing electrical powerlines as a transmission medium to provide high-speed communications capabilities by coupling radio frequency (RF) energy onto the powerline. The benefits of implementing this emerging technology are significant, starting from the fact that there is no need for new infrastructure, which is both time consuming and expensive to install. In addition, bearing in mind that no new wires are required, powerline communications techniques have become even more appealing. The advantage of using electric powerlines as the data transmission medium is that every building and home is already equipped with the powerlines that are connected to the power grid. The power line carrier (PLC) communication systems use the existing AC electrical wiring as the network medium to provide high speed network access points almost anywhere there is an AC outlet. In most cases, building a home network using the existing AC electrical wiring is easier than trying to run wires, more secure and more reliable than radio wireless systems like 802.11a/b/g, and relatively inexpensive as well. For most small office home office (SOHO) applications, PLC provides a convenient solution to current networking problems.

For many years, systems have been built to communicate low bandwidth analog and digital information over residential, commercial and high voltage power lines. Powerlines have been exclusively considered for the transmission of electricity in the past. However, with the emergence of modern networking technologies including broadband, there is a need for the utility and service providers to discover solutions that are able to deliver the services to the consumers at minimum cost and maximum performance. Only recently have companies turned serious attention to communicating over power lines for the purpose of data networking. The potential of the powerline as a ubiquitous medium to be able to deliver not only electricity or control signals, but even full duplex high-speed data and multimedia content, is being explored now. Since the developments in the field of powerline networking are fairly new, information about PLC techniques is largely dispersed. There is a lack of cohesive reference material that summarizes the existing technologies, available solutions, and technology trends in the field of powerline carrier communications.

1.2 Power Distribution Grid

The power distribution grid represents an omnipresent widely branched hierarchical structure. Generally, power outlets are found in every room of a building, hence a local area network is basically available and ready for use. Moreover, the structure of the entire low-voltage distribution grid, including outdoor supply cables, is most appropriate for data/Internet access, offering both last mile and last meter solutions.

For high-speed indoor networking, powerlines possess the key feature of being able to connect any point of interest with no need for new wires. Since indoor and outdoor power supply wiring are very different, usually different power line communications (PLC) systems for each of the wiring structures are required. They are denoted as indoor and access systems, respectively. However, some systems are able to communicate throughout the whole network, and do not distinguish between indoor and outdoor domains. Contrary to telephone wiring, the power line grid is a shared medium, so all end users have to share the available channel capacity. Besides the broadband applications there also exist narrowband applications of PLC covering frequencies in the kilohertz range. Such applications are used for switching and mains signaling purposes.

The transmission losses encountered over a power line grow with the square of the current ***(I^2),*** so it is important to keep the current (*I*) as low as possible, especially for long distances. A well-known optimizing technique is to choose as high a voltage as possible. This basic idea automatically generates a network hierarchy in terms of voltage: for long distance transportation very high voltage is used, which is stepped down to lower levels for shorter distances. Thus, similar power distribution grid structures are found all over the world.

- High voltage (HV) power lines or even extremely high voltage (EHV) lines emanate from power plants and represent a wide-meshed long-distance nationwide network. The term HV applies to voltages over 36 kV, while voltages over 300 kV are denoted EHV. The EHV and HV levels establish a transmission network strictly for power, since no customer premises are directly connected to the lines.
- The task of the next lower transmission level is bringing electrical power into cities, towns, and villages. Here medium voltage (MV) is used, constituting a finer meshed network in

comparison to HV. Medium voltage covers the range from 1 kV to 36 kV.

- Eventually, MV is transformed down to low voltage (LV) with levels below 1 kV for distribution to customer premises as shown in Figure 1.1. The LV grid represents a very fine-meshed network, precisely adapted to the density of consumer loads.

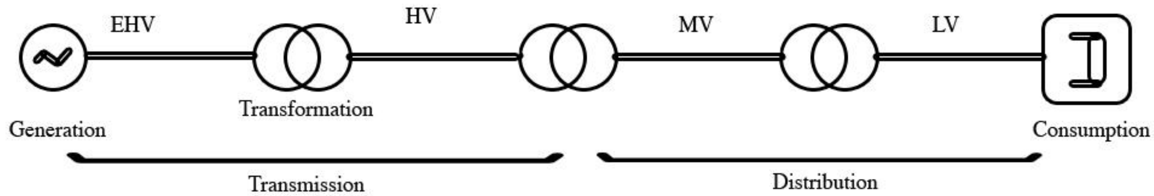

Figure 1.1 Voltage layers of a typical power distribution grid.

MV/LV transformer output power is transported over rather large service cables to the customer premises, where they end on a panel board. The panel board serves as a central bus bar from which the indoor wiring to various appliances and wall sockets starts.

In the following section the basic high frequency (HF) properties of power supply grids found in different industrialized countries are investigated with respect to their suitability for use with PLC.

1.2.1 European Power Supply Network

For the distribution of MV (e.g., 10 kV or 20 kV) either overhead wiring or buried cables are in use. In urban areas usually only buried cables are found. Typically MV cables are deployed in ring structures, so both ends are connected to the same MV bus bars. During operation the ring is usually opened so that two branches result. The loads connected to the medium voltage layer are MV/LV transformers providing 3-phase power. From the LV-bus bars service cables bring power to the customer's premises.

An MV/LV transformer provides up to 630 kVA, which is sufficient to supply several hundred households with power. Typically between 3 and 10 service cables emerge from one transformer substation, forming a tree-like structure. Sometimes rings and mesh topologies are also found. If necessary, large buildings or industrial plants are supplied directly with MV.

The LV windings of a transformer usually represent a Y-configuration, the center of which is grounded as shown in Figure 1.2. From phase-to-phase the voltage is 400 V, and 230 V from phase-to-neutral. In most European countries all three phases and the neutral are brought to the customer's panel board. Thus, the service cables include four conductors. Indoor PLC signals are injected between phase and neutral because not every building is equipped with a protective earth conductor. If there is a protective earth conductor available, it is short-circuited with the neutral conductor at the house service connection point. Thus, without modification of the grid structure it is impossible to use neutral and protective earth as signal conductors in the indoor domain.

The power distribution network of Great Britain differs slightly from that of continental Europe. The MV distribution operates at 6.6 or 11 kV. But an important difference with respect to service cables is the fact that, in general, only one phase and the neutral supply a building. Consequently, PLC signals must be injected between a phase and the neutral in the access domain.

A further difference concerns cable construction. While in continental Europe most cables contain four sectors, mostly sheathed concentric structures are found in Great Britain. Either the three phase conductors within the sheath have a concentric cross-section, or each phase conductor forms a 120° sector.

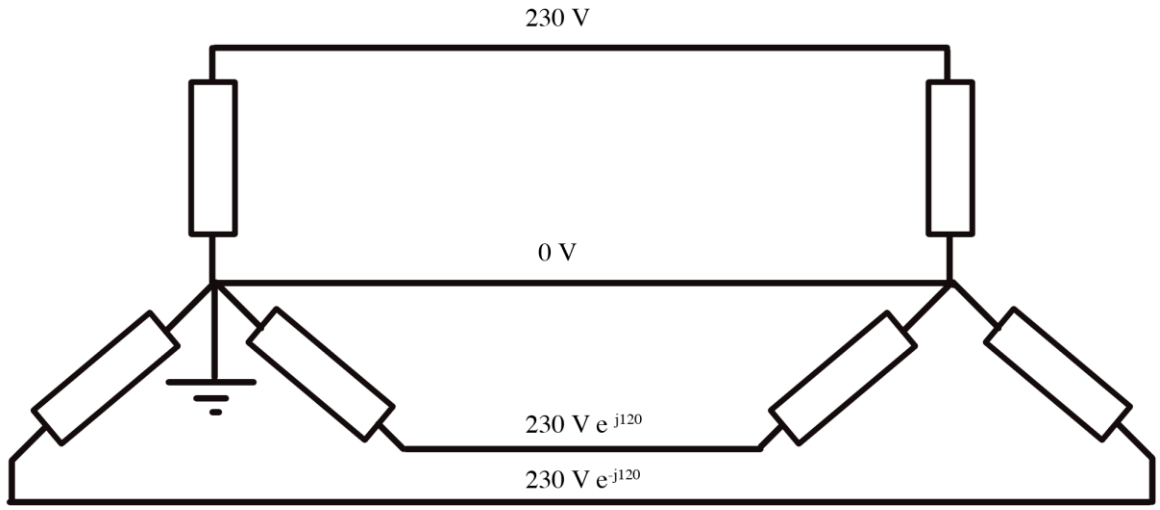

Figure 1.2 European low voltage distribution grid with transformer inductances and loads.

1.2.2 United States Supply Network

At the distribution level, typically 80 percent of the power lines are overhead in the United States. In urban areas most of the cables run underground. MV ranges from 4 to 34 kV, and the length of most lines varies between 10 and 30 miles. An MV distribution circuit consists of a three-phase main trunk. Depending on the load, a two-phase or one-phase tap extends into load areas. In less densely populated areas, MV circuits are fed by a single substation with standby backup from an alternate substation. In large cities, however, an underground mesh network is fed from multiple sources. Therefore, MV lines basically run along every street of a town or city. In direct neighborhood to buildings, single-phase transformers provide the LV, which is immediately passed to the buildings' panel boards. Transformers are often mounted on poles or located in special boxes next to a building. On the primary side the transformers are fed with one phase and neutral, while the secondary provides 240 V with a grounded center tap as depicted in Figure 1.3.

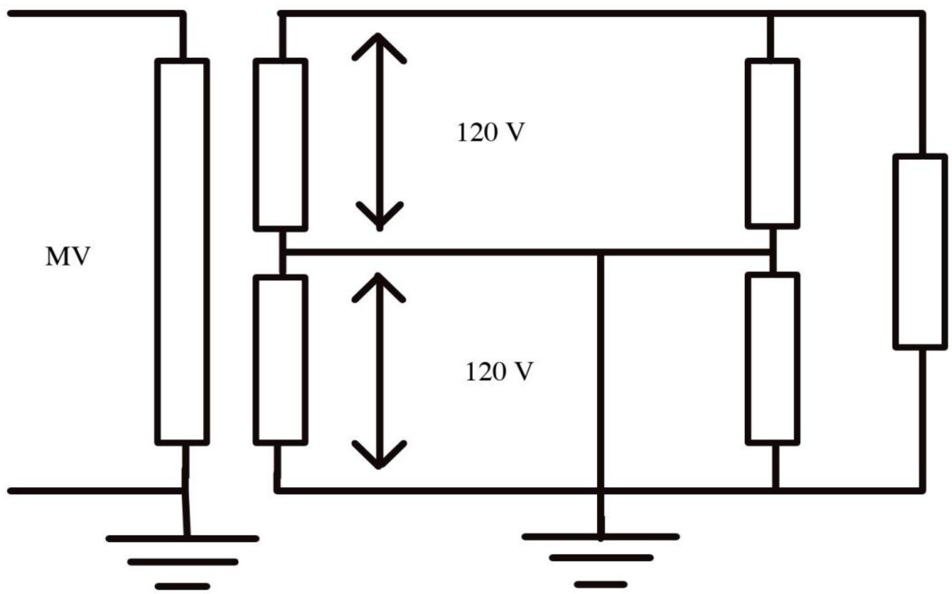

Figure 1.3 U.S. split phase system with MV/LV transformer and loads.

The length of a secondary circuit (LV level) is usually less than 300 m, with 1 to about 10 customers per transformer. Typically, in residential areas a customer receives power over three wires, providing 2 x 120V or 240 V. Standard loads are connected to the 120 V feeds, while large loads (e.g., heaters) use the 240 V level.

An access domain PLC system might be installed in the substation, feeding signals into the MV wires of the distribution circuit. However, as most electrical devices receive single-phase service only, the PLC signal must be injected between phase and neutral. Due to the significant attenuation realized by HF signals, transformer bridging will be necessary. Another possible scenario would be a hybrid approach connecting transformers, within the substation, to the telecommunications network (backhaul network comprising of internet, data and/or voice signals) via optical fibers and feeding the PLC signals into the secondary circuits of the transformers. The point of connection may be either at a power substation, or at an intermediate point between the substations, depending on the network topology. Figure 1.4 illustrates a PLC architecture [8] which utilizes this concept, the details of which are explained in Chapter 3.

Electric supply companies are utilizing fiber optics [7] to provide substantial data carrying capability, for themselves and for third party use, since the medium provides inherent isolating and insulating properties and immunity to electrical interference, and can be used along existing power networks. This way much higher data rates can be ensured since only a few customers have to share the medium.

Indoor PLC applications in the United States look very similar to those found in European with signals having to be injected between one phase and neutral at the 120 V level.

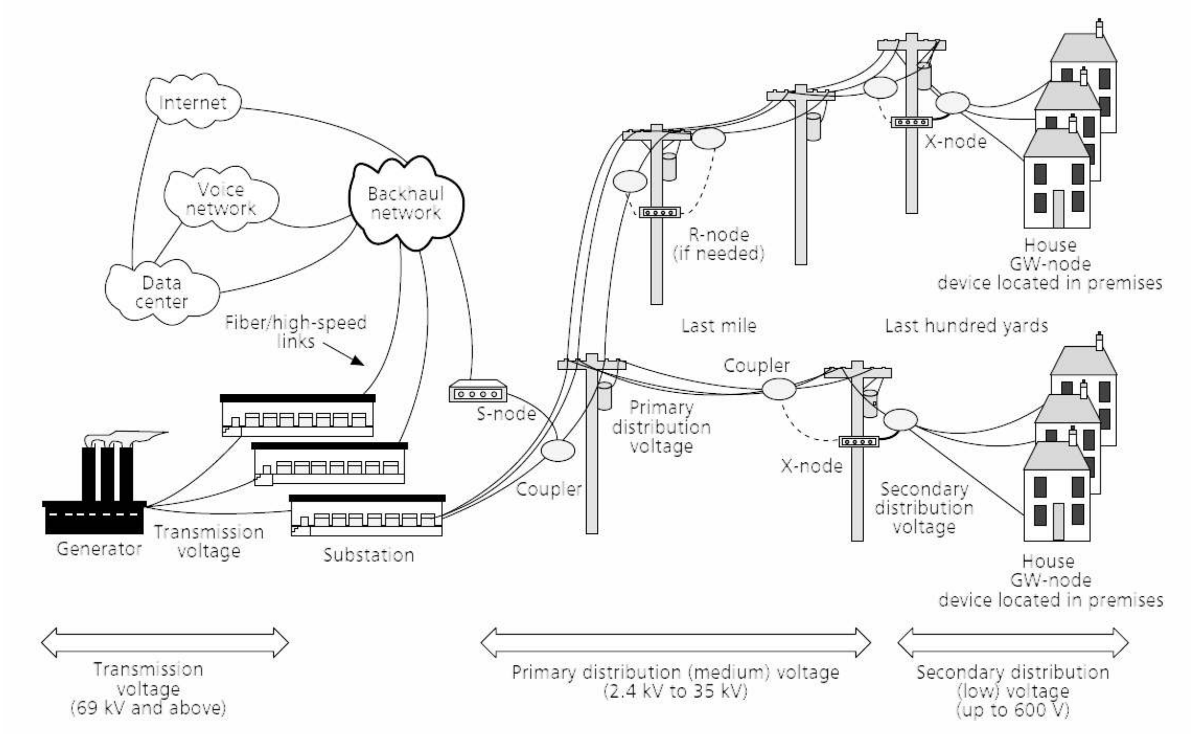

Figure 1.4 PLC system architecture adopting the hybrid approach [8].

1.2.3 Japanese Power Supply Network

The structure of the Japanese power supply grid is very similar to that of the United States power network. However, the HV level uses more than 22 kV, and at the MV level (i.e., from substation to transformer) 6.6 kV is the usual voltage applied. Similar to the United States, transformers are mounted on top of poles feeding two-phase secondary circuits with a neutral line, which is connected to a ground rod. Thus, the customer receives power over two or three wires at 100 or 200 V. Over 90 percent of the Japanese power supply network is comprised of overhead wiring. Mid- to large-scale housing units have their own MV/LV transformers inside the building. The typical length of an LV circuit is about 50-200 m. Up to 30 households are supplied by one transformer.

The number of households fed by one MV transformer substation is higher than in the United States. Thus, if PLC were deployed on the MV level, numerous customers would have to share the available system capacity. It is possible that unacceptably low data rates might result. Therefore, in Japan PLC would be most efficient to use on the LV distribution grid. As optical fibers are deployed along side of most Japanese MV lines, a powerful backbone network is already available there. Similar to the United States, most indoor loads are supplied from 100 V feeds, so once again the PLC signal must be injected between phase and neutral.

The previous sections reveal that the availability of the power distribution grids of industrialized countries generally exhibit excellent features for PLC-based fast data transmission, in order to establish cost-effective and competitive last mile solutions for everyone. In the following section the existing and emerging standards and regulations regarding PLC transmission are investigated.

1.3 Existing and Emerging Standards and Regulations

In this section the standards and regulations pertaining to the powerline communications are highlighted. Lack of centralized standardization has been one of the major factors behind the late deployment of powerline networks.

Due to the fact that PLC has to operate over a network with limited symmetry, a strong necessity for regulation arises to guarantee electromagnetic compatibility (EMC), especially in the context of how PLV may affect wireless services, and vice versa. This section discusses the current status of international standardization processes and presents the regulation initiatives underway in different countries.

1.3.1 Electromagnetic Compatibility

Electromagnetic Compatibility (EMC) resulting from the presence of wireless services is one of the crucial factors when PLC technology is commonly deployed. This section will present an overview in order to enlighten the highly complex connections, which in the past have led to various regulation issues.

At the outset, it should be noted that the cables comprising any power supply grid have been designed for nothing but electrical low-loss power transportation at frequencies of either 50 Hz or 60 Hz. Using them for PLC purposes means they will have to carry signals at frequencies between 9 kHz and 30 MHz. In these frequency ranges power cables become leaky, which means a part of the high-frequency signal power emanates in the form of electromagnetic radiation. Thus, power cables can be considered linear antennas with low efficiency.

Whenever PLC signals overlay the frequency ranges of used wireless services, interference may occur, the degree of which strongly depends on transmission power and distance as well as on the specific structure of the wiring. If, say, a broadcast radio receiver is located next to a power cable, disturbance is very likely, while at a distance of several meters almost no impact may be noticed. The fraction of injected signal power emitted in the form of radiation is determined by the symmetry of the network or its cables, respectively. Symmetry is defined in terms of the impedance between conductors and ground. If for a two-wire line the impedance between each conductor and ground is equal, the line is regarded as symmetrical or balanced. Balanced lines are necessary to achieve signal propagation in the desired differential mode, whereas lack of symmetry leads to an unwanted common mode. Common mode currents flow in parallel on both conductors, while the return portions take their way in the ground. Generally, common mode currents are responsible for the existence of electromagnetic radiation. Differential mode currents, on the other hand, are equal in magnitude and flow in opposite directions on the signal conductors. A highly symmetrical line is characterized by a large ratio of differential-to-common mode current, so such a line will exhibit only very weak electromagnetic radiation.

In order to minimize unwanted electromagnetic radiation from interfering with a PLC system, the following two basic steps are recommended:

Step 1.) The given symmetry of those power lines used for HF signal transportation should be exploited as far as possible or even improved by network conditioning.

On one hand, HF filters may he installed at the ends of lines in order to keep PLC signals on the desired propagation paths and prevent them from entering attached devices or conductors that have high radiation efficiency. Such filtering turns out to be very effective, but also costly. Therefore, many electric utilities refuse to install any kind of filters. Nevertheless, in the future very high-speed approaches to critical network structures filtering may be the only way to reduce electromagnetic radiation to permissible levels.

On the other hand, appropriate selection of conductors immediately leads to exploitation of the "natural" symmetry, which is found, for example, in four-sector supply cables. Since in continental Europe usually three phases are used to supply a building, the PLC signal may be injected between two phases. Using two phases for HF signal transportation leads to significantly higher symmetry than injecting the signal between a phase and neutral. However, this solution is limited to the access domain, and unfortunately, is not applicable to indoor networks. Due to the widespread use of four-sector cables, the German access domain appears much better suited to PLC than, say, networks in Great Britain, where usually only one phase and the neutral conductor supply a household service connection point.

As already mentioned, indoor networks unfortunately will not exhibit such natural symmetry, so signal injection must be established between the phase and neutral wires. Currently, however, investigations are underway to check injection possibilities between neutral and protective earth where less electromagnetic radiation is expected due to the greater amount of symmetry that is present.

Step 2.) Reduce the power spectral density (PSD) of PLC data transmission signals. Since PLC signal emissions are measured within a limited bandwidth, reducing PSD of PLC signals immediately leads to lower electromagnetic radiation levels, although the total transmission power remains unchanged. Therefore, it is advantageous to use broadband modulation schemes, which equally spread the transmitted power over large frequency ranges. The efficiency of this kind of spreading is, however, limited by the low-pass frequency response characteristics of the power line.

This section has outlined important aspects of needed EMC between PLC and wireless services. In practice, the necessary symmetry needed for reduced EMC is rather limited within the power supply grid. As a consequence, complete avoidance of unwanted electromagnetic radiation is simply infeasible. Moreover, besides for PLC, the symmetry of any communications network is limited (e.g., for telephone networks and cable TV as well as for computer LANs), so a certain amount of potential electromagnetic radiation must be assigned to each of them.

The current status of regulation encountered within various regions and countries is presented as follows.

EUROPE

Comité International Spécial des Perturbations Radioélectriques (CISPR) is the committee that establishes standards for controlling electromagnetic interference in electrical and electronic devices, and is a part of the International Electrotechnical Commission (IEC). CISPR activities are always closely observed by European regulatory bodies. This is because CISPR publications are intended to become harmonized European laws. After passing a voting process in CENELEC (*Comité Européen de Normalisation Électrotechnique)*, which is a European standardization body, CISPR publications become stringent law for each member country of the European Union.

Since the PLC standardization process in CISPR is still underway and not completed, national regulatory authorities (e.g., in Great Britain and Germany) have already instituted national legislation even at the risk of contradicting the outcomes of an eventual European harmonization process.

During 2001 the European Commission issued a mandate to CENELEC [5] and the European Telecommunications Standards Institute (ETSI) for elaborating a new standard for electromagnetic emissions from telecommunication networks. It can be expected that the new standard will specify limits of magnetic field levels at a distance of 3 m from the network under test.

The new European law is only used in case of compliance (interference). This means that the disturbing modem must be switched off if a listener of a radio service complains.

For very low-speed PLC systems, a frequency range from 3 kHz to148.5 kHz is available, according to standard EN50065 [6], which has been in force since 1991. The frequency range is divided into four bands (denoted A, B, C, and D) with detailed transmission signal amplitude limitations and usage. Due to the very restricted bandwidth, the maximum data rates attainable are in the range of 100 kbps.

UNITED STATES

In the United States the use of PLC is regulated by the Federal Communications Commission (FCC) Part 15 [4], which distinguishes between low-speed applications for signaling and switching purposes and high-speed data transmission.

Low-speed systems are allowed to operate at frequencies below 490 kHz. Compared to the European limitations currently under discussion, FCC Part 15 can he regarded as highly generous for high-speed PLC systems, and the FCC regulation is not obstructing the spread of PLC technology within the United States.

JAPAN

In Japan, the use of PLC systems is permitted in the frequency range 10 kHz - 450 kHz by the national Radio Law and its supplementary provisions. This frequency range is obviously useful for low-speed PLC systems (i.e., basically for mains signaling, switching, or simple control and supervision tasks). Furthermore, similar to Europe, sub-bands are specified within the frequency range with detailed rules for use and the limitation of signal transmission levels.

PLC systems operating at higher frequencies (e.g., up to 30 MHz) are currently not permitted. Japan is carefully watching the progress of the regulations being developed within CISPR, so as to possibly adopt the outcomes in order to allow PLC systems to operate at higher frequencies in the near future.

Eventually PLC data transmission systems may evolve into a technology of worldwide interest. Hence, the regulation of such a new technology is currently an important matter being considered by many international bodies. Given the tremendous effort actually being made towards embedding PLC into existing EMC rules as a new communications technology, it can be expected that in the near future widespread, legal deployment of PLC systems is possible worldwide.

1.3.2 EU Standard (EN 50065)

For Western Europe (i.e. the countries forming the European Union plus Iceland, Norway and Switzerland) the regulations concerning RPC (Residential Power Circuit) are described in CENELEC standard EN 50065 entitled “Signaling on low-voltage electrical installations in the frequency range 3 kHz to 148.5 kHz.” In Part 1 of this EN-standardization-paper, entitled “General requirements, frequency bands and electromagnetic disturbances” [1], the allowed frequency band and output voltage for communications over the RPC are specified. The frequency range, which is allowed for communications, ranges from 3 kHz to 148.5 kHz and is subdivided into five sub-bands (four sub-bands are denoted A, B, C and D). The usage of these sub-bands is described in Table 1.1 and their detailed specifications are as follows:

● For the frequency band from 3 kHz – 9 kHz: The transmitter should be connected to a 50 Ω // (50 µH + 1.6 Ω) RPC -simulation-circuit. In principle the transmitter output voltage should not exceed 134 dB (µV) ≈ 5 V.

● For the frequency band from 9 kHz – 95 kHz: The transmitter should be connected to a 50 Ω // (50 μH + 5 Ω) RPC-simulation-circuit. Different maximum transmitter output voltages apply for a narrow-band (i.e., a 20 dB bandwidth of less than 5 kHz in width) and Broad-Band transmitters (i.e., a 20 dB bandwidth of more than 5 kHz in width).

● For Narrow-Band signals the maximum allowed peak voltage at 9 kHz equals 134 dB (μV) ≈ 5 V, exponentially decreasing to 120 dB (μV) ≈ 1 V at 95 kHz. However, for Broad-Band signals, the maximum allowed peak voltage equals 134 dB (μV).

Furthermore, in any frequency band of 200 Hz in width, the maximum transmitter output voltage should not exceed 120 dB (μV).

● For the frequency band from 95 kHz - 148.5 kHz: the transmitter output voltage should not exceed 116 dB (μV) ≈ 0.63 V. In certain cases an exception can be made allowing 134 dB (μV).

CENELEC has started working on a new standard for frequencies up to 30 MHz. This will allow high-speed digital access to consumer's premises via the electric utility wiring. The details of which are described in [2].

Band	Frequency Range	Usage
	3 kHz – 9 kHz	Limited to energy providers; However, with their approval it may also be used by other parties inside the consumer premises. *(No "letter" description exists, due to the fact that this band was defined at a later stage)*
A-band	9 kHz – 95 kHz	Limited to energy providers and their concession holders.
B-band	95 kHz – 125 kHz	Limited to energy provider's customers; No access protocol is defined for this frequency band.
C-band	125 kHz – 140 kHz	Limited to energy provider's customers; In order to make simultaneous operation of several systems within this frequency band possible, a carrier-sense multiple access protocol using a center frequency of 132.5 kHz was defined.
D-band	140 kHz – 148.5 kHz	Limited to energy providers customers; No access protocol is defined for this frequency band.

Table 1.1 CENELEC frequency range usage.

1.3.3 US Standard (IEEE P1901)

The Institute of Electrical and Electronics Engineers (IEEE) formed the IEEE P1901 working group in June 2005 to develop a global standard for high-speed powerline communications. The IEEE P1901 working group has more than 50 members including corporations, government agencies, trade associations, universities, as well as standards organizations. This working group will develop a standard for high speed (>100 Mbps at the physical layer) communication devices via alternating current electric power lines, so called Broadband over Power Line (BPL) devices [3].

The standard will use transmission frequencies below 100 MHz. This standard will be usable by all classes of BPL devices, including BPL devices used for the first-mile/last-mile connection (<1500m to the premise) to broadband services as well as BPL devices used in buildings for LANs and other data distribution (<100m between devices). This standard will focus on the balanced and efficient use of the power line communications channel by all classes of BPL devices, defining detailed mechanisms for coexistence and interoperability between different BPL devices, and ensuring that desired bandwidth and quality of service may be delivered. The standard will address the necessary security issues so as to ensure the privacy of communications between users and allow the use of BPL for security sensitive services. This standard is limited to the physical layer and the medium access sub-layer of the data link layer, as defined by the International Organization for Standardization (ISO) Open Systems Interconnection (OSI) Basic Reference Model. The effort will begin with an architecture investigation, and this will form the basis for detailed scope of task groups that will work within P1901 to develop the components of the final standard.

The working group has created, reviewed and completed draft version 4.01 of the standard on August 2010. Draft 4.01 was submitted to the IEEE-SA Standards Board for consideration as an IEEE standard. On September 30, 2010, the IEEE-SA Standards board approved the IEEE Std 1901-2010 as an IEEE standard for Broadband over Powerline Networks.

1.3.4 Federal Communications Commission

The Federal Communications Commission (FCC) is an independent agency of the United States government working in areas of broadband, the spectrum, the media, public safety and homeland security. The FCC is responsible for regulating all non-federal government use of the radio spectrum (including radio and television broadcasting), and all interstate telecommunications (wire, satellite and cable) as well as all international communications that originate and terminate in the United States.

Broadband over Powerline (BPL) is the term coined by the FCC for new (BPL) modems used to deliver IP-based broadband services on electric powerlines. On April 23, 2003, the FCC adopted a *notice of enquiry* (NOI) [9] seeking public comment and expressing enthusiasm about the potential of the BPL technology to enable electric powerlines to function as a “third” wire in the home, and create competition with the copper telephone wire line and cable television coaxial cable wire line. Numerous organizations weighed in with comments both in support and opposition.

One of the immediate concerns of the FCC over the widespread use of BPL products is the impact in terms of radio frequency noise. The FCC is more concerned about the interference potential of BPL signals transmitted on exposed, overhead medium voltage power lines. Interference issues between unlicensed devices, including BPL modems, and other electronic devices are governed by Part 15 of the FCC rules. All electronic devices sold in the United Sates have to meet RF emissions limits set by the FCC.

On October 14, 2004, the FCC adopted rules to facilitate the deployment of “Access BPL” that is, use of BPL to deliver broadband services to homes and businesses. Furthermore, in August 2006, the FCC adopted a memorandum opinion and an order on broadband over powerlines, giving the go-ahead to promote broadband services to all Americans [10]. Moreover, at that time, the FCC chief Kevin Martin said that BPL "holds great promise as a ubiquitous broadband solution that would offer a viable alternative to cable, digital subscriber line, fiber, and wireless broadband solutions", and that BPL was one of the agency's "top priorities" [11]. Hence, the FCC was able to propose rules which would govern BPL in a manner similar to the rules applicable to personal computers and other digital devices.

1.3.5 HomePlug Powerline Alliance

Founded in 2000 by 13 industry leaders (3Com, AMD, Cisco Systems, Compaq, Conexant, Enikia, Intel, Intellon, Motorola, Panasonic, Radio Shack, SONICblue, and Texas Instruments) the HomePlug Powerline Alliance enables and promotes the rapid availability and adoption of cost effective, interoperable and standards-based home powerline networks and products.

Members of the HomePlug alliance tested the technology in an extensive field trial of 500 homes throughout North America. Based on the success of this field trial, the completion of the HomePlug 1.0 Specification was announced in June 2001.The first publicly available HomePlug products were demonstrated in early 2002 at the CES and CeBIT exhibitions. At these shows, HomePlug member companies unveiled HomePlug-compliant home networking products such as bridging and routing devices, network interface cards, and combination 802.11b access point/powerline.

The HomePlug 1.0 protocol is highlighted in [13] and [69] as follows: HomePlug 1.0 uses a Physical Layer (PHY) protocol based on equally spaced, 128-carrier Orthogonal Frequency Division Multiplexing (OFDM) from 4.5 MHz to 21 MHz, in conjunction with concatenated Viterbi and Reed Solomon coding with interleaving for payload data and turbo product codes for control data. A total of 84 carriers are used to transmit data. Modulation formats such as BPSK, DBPSK, DQPSK or ROBO (a robust form of DBPSK) are used for data and a cyclic prefix is used for synchronization.

A pair of nodes first determines which subcarriers are usable, and what form of modulation and error correction should be applied to the channel. This ‘tone map’ is used for subsequent communication between the nodes. Broadcast packets and frame delimiters use all subcarriers with robust modulation and forward error correction codes so that all nodes are able to interpret them, the rest of a unicast frame uses the higher speed specified by the tone map.

The presence of large attenuation prevents the detection of collisions, so HomePlug 1.0 uses CSMA/CA for its MAC protocol. Powerline modules determine if the medium is idle or not, using virtual carrier sense (VCS). If it has been idle for Extended InterFrame Space (EIFS), the station can send the segment without contention. If it is busy, it waits for CIFS (Contention InterFrame Space) or RIFS (Response InterFrame Space) after the end of the current transmission. The delimiter informs the listening node's VCS when the transmission will end and whether a response is expected, for synchronization. The receiver sends ACK, NACK (or NAC), or FAIL after RIFS when it is needed, taking top priority. ACK indicates successful delivery, while NACK (or NAC) indicates an error detected at the receiving end. FAIL indicates that the receiver was unable to buffer the segment. Otherwise, stations wait until the end of the CIFS period. Then they use two priority resolution slots to select the highest priority level traffic waiting. Nodes with this traffic contend for the medium during the contention window using a randomly selected delay. Initially, there are eight contention resolution slots, and upon collision, nodes increase this to 16, then 32, according to a backoff schedule. Large contention windows are used to avoid costly collisions. In the case of frame control errors or collision, stations must wait for EIFS.

The HomePlug PHY occupies the band from about 4.5 MHz to 21 MHz. The PHY includes reduced transmitter power spectral density in the amateur radio bands to minimize the risk of radiated electromagnetic energy from the power line interfering with these systems. The raw bit rate using DQPSK modulation with all carriers active is 20 Mbps. The bit rate delivered to the MAC by the PHY layer is about 14 Mbps [69].

The HomePlug Powerline Alliance is a not-for-profit corporation established to provide a forum for the creation of open specifications for high-speed home power line networking products and services.

Products conforming to the HomePlug standards are designated as “HomePlug-certified products” [14] and they are entitled to use the official “HomePlug certification mark”. HomePlug, which has grown to more than 90 member companies, has chosen Intellon’s PowerPacket technology [68] as the baseline upon which the alliance’s first industry specification is build. HomePlug devices account for more than 80 percent of the world’s broadband powerline communications market and over 45 million devices have shipped to date.

1.3.6 Other Standards related to Powerline Communications

Other regulatory standards pertaining to powerline carrier communications include:

● The IEC 870 international standard on telecontrol, teleprotection and associated telecommunications for electrical power systems, as well as the IEC 1107 and 1142 standards pertaining to equipment for electrical energy measurement and load control [78].

● The CENELEC ENG1107 standard specifies equipment for electrical energy measurement and load control [79].

● The Consumer Electronics Association (CEA) R7 Home Network Committee [15] [30] ensures that the current and future Home Networks can coexist within a home and share information through the use of industry standard interfaces.

● The International Electrotechnical Commission (IEC) has standardized the distribution line communications (DLC) through Technical Committee No 57 (Power System Control and

Associated Communications), Working Group 9 (Distribution automation using distribution line carrier systems). All systems discussed in IEC TC57/WG9 use frequencies below 150 kHz [17].

● The PLCforum [40] is a leading international Association that represents the interests of manufacturers, energy utilities and research organizations active in the field of access and in-home PLC technologies. Since its creation in Interlaken (Switzerland) at the start of 2000, the number of members and permanent guests has increased and today totals more than 60.

● ETSI (the European Telecommunications Standards Institute) [18] is a non-profit organization whose mission is to produce the telecommunications standards that will be used for the decades to come throughout Europe and beyond. Based in Sophia Antipolis (France), ETSI unites nearly 700 members from 50 countries inside and outside Europe, and represents administrations, network operators, manufacturers, service providers, technical bodies and users. ETSI technical specifications on Powerline Telecommunications (PLT) are highlighted in [19] [20] and [21].

1.4 Current State-of-the-Art

PLC technology can be used for home networking applications to interconnect networked peripherals such as home computers, as well as any home entertainment devices that have an Ethernet port. Consumers can buy powerline adapter sets at most electronics retailers and use those to establish a wired connection using the existing electrical wiring in the home. These powerline adapters plug into a wall and then are connected to the home’s router via Ethernet cable. Additional adapters can be plugged in at any other outlet to give instant networking and Internet access to an Ethernet-equipped device.

The most established and widely deployed powerline networking standard for these powerline adapter products is from the HomePlug Powerline Alliance. HomePlug AV is the most current of the HomePlug specifications and was adopted by the IEEE P1901 group as a baseline technology for their standard, published December 30, 2010.

PLC systems have long been a favorite at many electric utility industries because it allows them to reliably move data over an infrastructure that they control. Interest in this application has grown substantially because there is a growing demand in obtaining up-to-the-minute data from all metered points in order to better control and operate the system. PLC is one of the technologies being used in Advanced Metering Infrastructures (AMI) systems [76]. AMI are systems that measure, collect and analyze energy usage, and communicate with metering devices such as electricity meters, gas meters, heat meters, and water meters; either upon request, or according to a set schedule.

Powerline technology can also enable in-vehicle network communication of data, voice, music and video signals by digital means over direct current (DC) battery powerline. Advanced digital communication techniques tailored to overcome hostile and noisy environment are implemented in a small size silicon device. One power line can be used for multiple independent networks. Prototypes are successfully operational in vehicles, using automotive compatible protocols such as CAN-bus [46].

1.5 Thesis Outline

The remainder of this thesis is organized as follows. In Chapter 2, an overview of various digital data communication techniques relevant to this study are presented which are useful for the PLC system modeled in Chapter 6. In Chapter 3 the potential of home networking and automation is explored along with limitations and applications. Various economic and technical aspects of home networking are presented and the available technologies compared. A special focus is given to the powerline networking and a technical description of the powerline networking technology is presented. This chapter gives a general overview and applications of powerline networking technologies being used in practice. In Chapter 4 the powerline as a communication channel is discussed. Different approaches for modeling the powerline channel are described. An introduction to a multipath channel model is presented. The channel is described in more detail in Chapter 6. Various transmission impairments and factors governing the powerline for data transmission are studied. Modulation schemes mentioned in Chapter 2 are described in more detail which are used in practical PLC systems. Chapter 5 presents a technical discussion of all the major technologies in the powerline networking area is presented. The technologies are studied in depth and their major working principles and characteristics are highlighted. In Chapter 6 a candidate PLC communications system is described and modeled. The multipath channel model introduced in Chapter 4 is described in detail and used for the performance evaluation of the candidate PLC system model. The characteristics of the reference channels used in our system are also analyzed and compared with those found in literaturel. In this chapter we study and evaluate the performance characteristics of powerlines as a communication channel for data transmission. We also compare the simulated PLC system performance results with those reported in literature and draw conclusions. Chapter 7 presents the conclusions of this study.

2. Data Communication Techniques

This chapter focuses on various, albeit a limited number of, data transmission techniques commonly used in practice. The presentation is intended to give only a general review of some basic data communication signaling methods.

Analog and digital formats are means used to move information across any medium. The physical layer of a system is responsible for transportation of a raw bit stream from one node to another. For actual data transmission, various physical media can be used (including magnetic media, twisted pair, baseband coaxial cable, broadband coaxial cable, fiber optic, powerline, wireless or radio, microwave, satellite etc.). However, for the purpose of this work, focus is placed on the data transmission techniques related to the powerline environment.

2.1 Baseband Digital Signals

A baseband waveform has a spectral magnitude characteristic that is nonzero for frequencies in the vicinity of $f = 0$, and it has negligible spectral content elsewhere.

2.1.1 Line Coding

Line coding is a method of making signal regeneration more reliable. Binary 1's and 0's may be represented in various serial-bit signaling formats know as line codes. The two major categories of line codes are return-to-zero (RZ) and non-return-to-zero (NRZ). With RZ coding the waveform returns to a zero volt level during a portion (usually one-half) of the bit interval. The waveform for the line code is further classified according to the rule that is used to assign voltage levels to represent binary data. Following are some of the waveform types:

Unipolar Signaling: In positive logic unipolar signaling, a binary 1 is represented by a high voltage level (positive voltage) and a binary 0 is represented by a zero voltage level. This type of signaling is also called as on-off keying.

Polar Signaling: Binary 1's and 0's are represented by positive and negative voltage levels each having the same magnitude.

Bipolar Signaling: Binary 1's are represented by alternately positive or negative values. The binary 0 is represented by a zero level.

Manchester Signaling: Each binary 1 is represented by a positive half-bit period pulse which is followed by a negative half-bit period pulse. Similarly, a binary 0 is represented by a negative half-bit period pulse followed by a positive half-bit period pulse. Manchester signaling is very popular because it combines the clock and the message into one signal. Manchester signaling is also known as the split phase encoding.

Figure 2.1 presents a graphical, time-domain comparison of the various line coding formats described above. Each of the line codes has certain advantages and disadvantages associated with it. For example, the unipolar NRZ line code has the advantage of using electronic circuits that only require one power supply, but it has the disadvantage of requiring channels that are DC coupled (i.e. frequency response down to f=0) since the signal has a non-zero DC value. The Manchester code combines the data and clock signal, which is beneficial for receiver synchronization. The Manchester code, however, occupies a significantly larger bandwidth because of the greater number of transitions involved at each signaling interval.

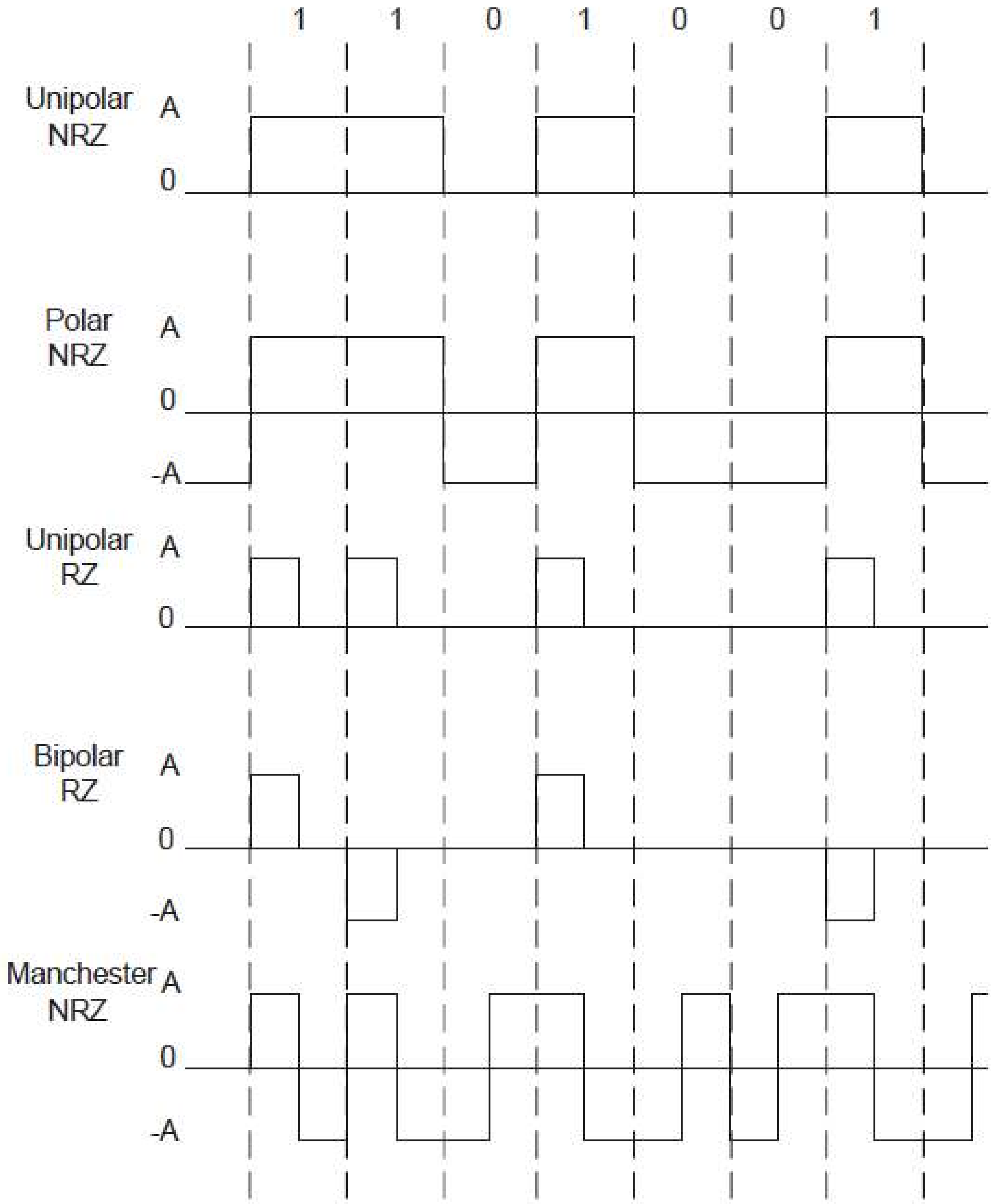

Figure 2.1 Comparison of Digital Line Code waveforms.

2.1.2 Multilevel Line Coding

The line codes described in the previous section only use two logical levels. If the signal has more than two possible values, then the signal is known as a multilevel signal. One way to reduce signaling bandwidth is to convert a binary signal to a multilevel signal. In practice, filtered multilevel signals are often used to modulate a carrier for transmission of digital information over a communication channel that possesses a relatively narrow bandwidth.

2.1.3 Network Synchronization

Synchronization is imperative in a digital transmission system. Any digital network requires that synchronization between the sender and receiver must be maintained. Synchronization signals are clock-type signals that are necessary within a receiver (or repeater) for detection of the data from the input signals. If the timing of arrival or transmission is misaligned, then the information will be distorted. Regardless of whether voice, data, video, or image traffic is present, the correct recovery of a digital stream of 1's and 0's at the receiver is contingent on proper signal timing being established between the two ends.

The clock-signals have a precise frequency and phase relationship with respect to the received input signal, and they are delayed when compared to the clock signals at the transmitter since there is propagation delay through the channel.

There are number of ways to synchronize signals within a digital network. Communication of digital data usually needs at least three types of synchronization signals to be employed:

- bit sync is used to distinguish one bit interval from another;
- frame sync is needed to distinguish groups of data;

• carrier sync is required for band pass signaling used in conjunction with coherent detection at the receiver.

Systems are designed so that the synchronization is derived either directly from the transmitted signal or from a separate channel that is used only to transmit the sync information. Systems with bit synchronizers that derive the sync directly from the corrupted signal need a sufficient number of alternating 1's and 0's in the data to be able to maintain the synchronization. The loss of synchronization that may occur when long strings of 1's or 0's is transmitted can be prevented by adopting one of the following alternatives:

• Bit interleaving (i.e., scrambling): in this case the source data with strings of 1's and 0's are scrambled to produce data with alternating 1's and 0's;

• Bit stuffing: if a certain number of 1's or 0's (e.g., 5) are transmitted repeatedly in succession, then the transmitter automatically inserts a bit of opposite value. The receiver later removes such bits that were stuffed into the data stream;

• Changing to a completely different type of line code that does not require alternating data for bit sync. Manchester NRZ can be used, but it requires a channel with twice the bandwidth of that needed for a polar NRZ line code.

Clocking or timing differences between the transmitter and receiver can exist. Therefore, while the receiver is expecting a bit that the transmitter has not sent, a slip occurs. Slips are likely to be present because of multiple factors in any network. This can result from the two clocks at the transmitter and receiver end being off or from problems that can occur along the link. Problems along the link can be accommodated however, using pulse stuffing or other techniques. Each device along the link has a buffer capability, creating a simple means of maintaining synchronization. Pulse stuffing can be done independently for each multiplexer along the way, enhancing overall reliability of the network, with the disadvantage of creating an undesirable overhead at each multiplexer.

2.2 Signal Modulation Techniques

Modulation is a technique that enables an information signal to be transferred by changing the characteristics of an electric signal carrier. Modulation is used both for analog and digital information. In the case of analog information, the carrier is affected continuously (soft transitions). In the case of digital information, the carrier is affected in a step-by-step fashion (state changes). The operational unit in a communication system performing modulation and the corresponding demodulation is called a *modem*. In analog transmission of information, both amplitude modulation and frequency modulation are used.

2.2.1 Amplitude Modulation

Amplitude Modulation (AM) is the simplest form of modulation. The amplitude of the carrier wave is varied in accordance with the voltage characteristic of the modulating signal (which may be analog or digital). An AM signal can be represented mathematically according to the relationship

$$S(t) = A_c[1 + m(t)]\cos\omega_c t \tag{2.1}$$

where, m(t) is the modulating signal, ω_c is the carrier frequency, and A_c is a constant.

Amplitude modulation is used to transmit analog voice (300 - 3,400 Hz) modulated on radio frequencies around 450 MHz in the mobile radio system NMT 450 (a 1G analog cellular radio technology employing frequency division multiple access (FDMA) to derive 200 channels with a width of 25 kHz), and to transmit TV images in cable-TV networks. The bandwidth of an AM signal is twice the bandwidth of the modulating signal. That is because amplitude modulation results in two sidebands on either side of the carrier frequency. The frequencies above the carrier frequency constitute the upper sideband, and frequencies below constitute the lower sideband. Single Side Band (SSB) modulation techniques exist that suppress one of the sidebands with the resulting SSB-AM signal having the same bandwidth as the modulating, or message, signal.

2.2.2 Frequency Modulation and Phase Modulation

Frequency modulation (FM) is used for broadcasting on the FM radio band, the sound channel for TV, and certain mobile communication systems. Phase modulation (PM) and frequency modulation are special cases of angle-modulation signaling. An angle-modulated signal is represented by

$$s(t) = A_c \cos[\omega_c t + \theta(t)] \tag{2.2}$$

where, $\theta(t)$ is the instantaneous phase conveying the message signal.

For PM, the phase is directly proportional to the modulating signal

$$\theta(t) = D_p m(t) \tag{2.3}$$

where $m(t)$ is the modulating signal and D_p is the phase-sensitivity of the phase modulator

For FM, the phase is proportional to the integral of $m(t)$ given according to

$$\theta(t) = D_f \int_{-\infty}^{t} m(\sigma) d\sigma \tag{2.4}$$

where, D_f is the frequency deviation constant, and now the instantaneous frequency of the carrier waveform conveys the message signal.

In particular, instantaneous frequency varies about the assigned carrier frequency f_c directly proportional to the modulating signal $m(t)$.

The instantaneous frequency is the frequency that is present at a particular instant of time and should not be confused with the term frequency as used in the spectrum of the FM signal. Thus the spectrum shows what frequencies are present in the FM modulated signal over all time. Figure 2.2 graphically illustrates the concept of AM and FM.

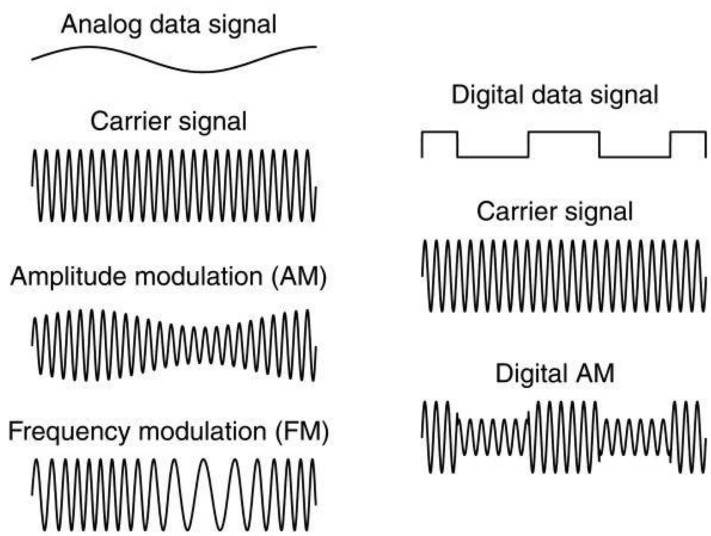

Figure 2.2 Amplitude and Frequency Modulation.

2.3 Digital Transmission of Information

Modulation makes it possible to transmit digital, binary information (1's and 0's) on analog carriers (such as radio and light waves). Digital transmission is, in effect, analog transmission of digital information. In the modulation process, a bit or a group of bits is translated into rapid state changes, such as amplitude or phase changes of a carrier waveform. Digitally modulated band pass signals are generated by using AM, PM, FM, or QAM (quadrature amplitude modulation) signaling. For digitally modulated signals, the modulating signal, *m*(t) is a digital signal given by a particular binary or multilevel line code. The basic modulation methods include: amplitude shift keyed (ASK) modulation; frequency shift keyed (FSK) modulation; and phase shift keyed (PSK) modulation.

In many cases, the purpose of modulation is to represent as many bits of information as possible per hertz of a carrier waveform. Such carriers include a band pass filtered telephone line (300 Hz - 3400 Hz) or a limited radio frequency band.

2.3.1 Shift Modulation

Figure 2.3 illustrates how amplitude, frequency or phase shift keyed modulation conveys digital information.

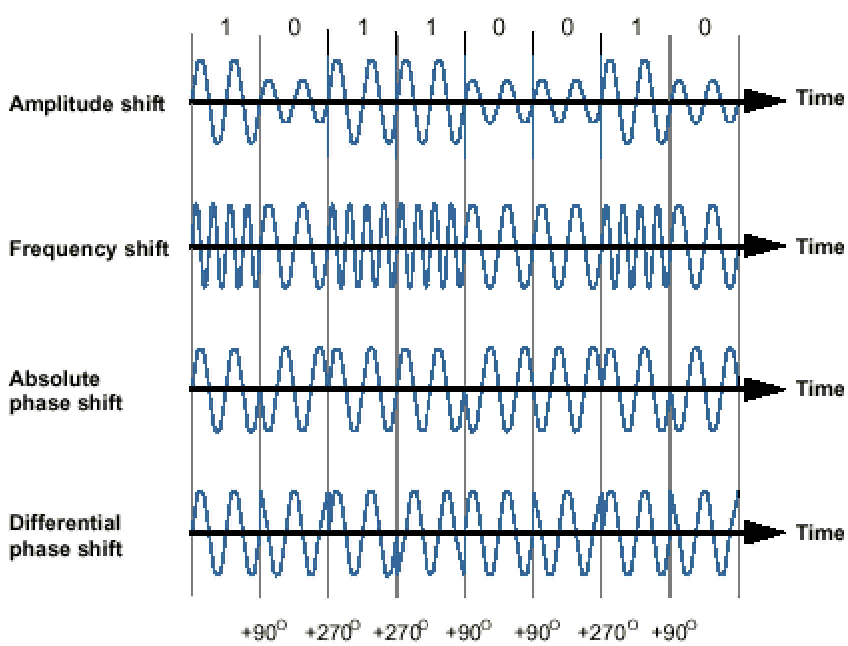

Figure 2.3 Shift modulation for digitally transmitted information.

In PSK modulation, the phase is shifted either differentially relative to the previous phase (for example, +90° for bit 0, and +270° for bit 1), or absolutely, in which case each modulation state is represented by a specific phase (0° for bit 0, and +180° for bit 1) relative to an initial phase (one that is known both by the transmitter and the receiver). The differential PSK technique permits less complicated demodulation equipment, and is therefore, more common.

An uncomplicated variant of amplitude modulation is used for optical fiber transmission: light on (full amplitude) or light off (no amplitude). On-Off keying (OOK) is a popular form of an AM signal. The approach is to let the carrier waveform represent a binary 1, and the absence of the carrier waveform represents a binary 0. Since OOK is an AM-type signaling scheme, the required bandwidth of an OOK signal is 2 times the bit rate. That is, the transmission bandwidth, B_t of the OOK signal is $B_t = 2B$ where B is the bandwidth of the modulated signal. Figure 2.4 below illustrates the use of light modulated by OOF in an optical fiber.

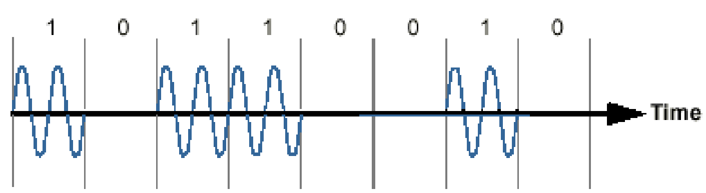

Figure 2.4 On/Off modulation of light in an optical fiber.

2.3.2 Bit Rate and Modulation Rate

There is a distinction between bit rate and modulation rate. Bit rate is specified by the unit bit/s - that is, by the number of ones and zeros transferred per second. Modulation rate specifies the number of possible state changes per unit of time. The unit baud, which is a less complicated way of expressing "modulation states per second," is used for modulation rate.

If a modulation method is used that comprises four different states, then each state can represent a combination of two bits, and all the combinations 00, 01, 10 and 11 must be uniquely represented. Figure 2.5 illustrates this concept.

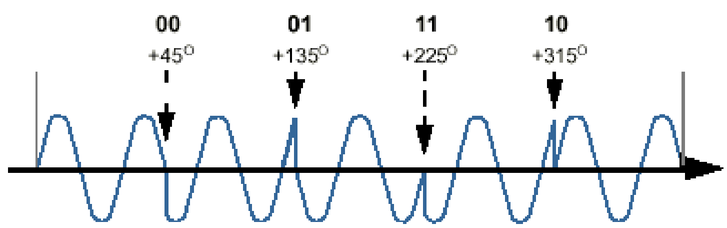

Figure 2.5 A PSK modulated signal having four distinct states.

Since each state change represents two bits, the baud value is half the bit/s value. For example, in modems where four different phase-shift states are used, a transmission signal operating at 1,200 baud equals the signaling bit rate 2,400 bit/s.

Accordingly, 16 different modulation states, or four bits per state, at the same bit rate of 2,400 bit/s would correspond to the modulation rate of 600 baud.

2.3.3 Higher Order Modulation

In many cases, the basic methods of amplitude-, phase- and frequency-shift modulation are combined. The combination of ASK modulation and PSK modulation is called quadrature amplitude modulation (QAM). This combination permits more bits per hertz to be communicated compared to either method used by itself. If the transmitter is a PM transmitter with an M-level digital modulation signal, M-ary phase-shift keying (MPSK) is generated at the transmitter output. A plot of the permitted values of the complex envelope would contain M points, one value for each of the M multilevel values, corresponding to the M phases that the signal is permitted to have. The case of M=4 is called Quadrature Phase Shift Keyed (QPSK) signaling. QAM signal constellations are not restricted to having allowed signaling points that lie only on a circle, as is required in the case of MPSK. The general QAM signal is defined according to

$$s(t) = x(t)\cos\omega_c t - y(t)\sin\omega_c t. \tag{2.5}$$

Figure 2.6 depicts a QAM with 16 modulation states that are combinations of eight phase-shifts and eight amplitudes.

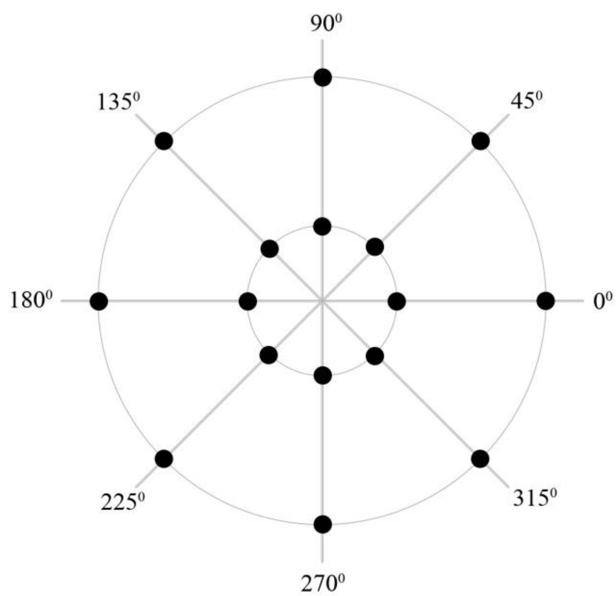

Figure 2.6 A 16 QAM signaling scheme with 16 modulation states.

2.4 Spread Spectrum Systems

Spread Spectrum (SS) uses wide band, noise-like signals to communicate message signals which makes the signals hard to detect. Spread signals are intentionally made to be much wider band than the information they are carrying to make them more noise-like. Spread Spectrum signals are harder to jam (intentionally interfere with) than narrowband signals. The features of *low probability of intercept* (LPI) and *anti-jam* (AJ) features are why Spread Spectrum techniques have been used by the military for many years [22].

Many types of SS systems exist. To qualify as a SS system, two system criteria should be met. Firstly, the bandwidth of the transmitted signal, $s(t)$, needs to be much greater than that of the message $m(t)$. Secondly, the relatively wide bandwidth of $s(t)$ must be caused by an independent modulating waveform $c(t)$, called the spreading signal. The signal c(t) must be known by the receiver in order for the message signal to be detected.

The two most common types of SS modulation techniques are Direct Sequence (DS) and Frequency Hopping (FH).

2.4.1 Direct Sequence Spread Spectrum (DS-SS)

The basic principle of direct sequence spread spectrum (DS-SS) is to spread the signal over a larger frequency band by multiplexing it with a signature, or code, signal. The system works over a fixed channel. To spread the signal, each bit of the packet to be transmitted is pre-modulated by a code. At the receiver, the original signal is recovered by receiving the entire spread signal and demodulating using the same code waveform c(t). Any narrowband interferer will appear much weaker to a direct sequence system since it uses only a small part of the total bandwidth used by the system. Figure 2.7 illustrates the transmitted frequency spectrum of a DS-SS signal.

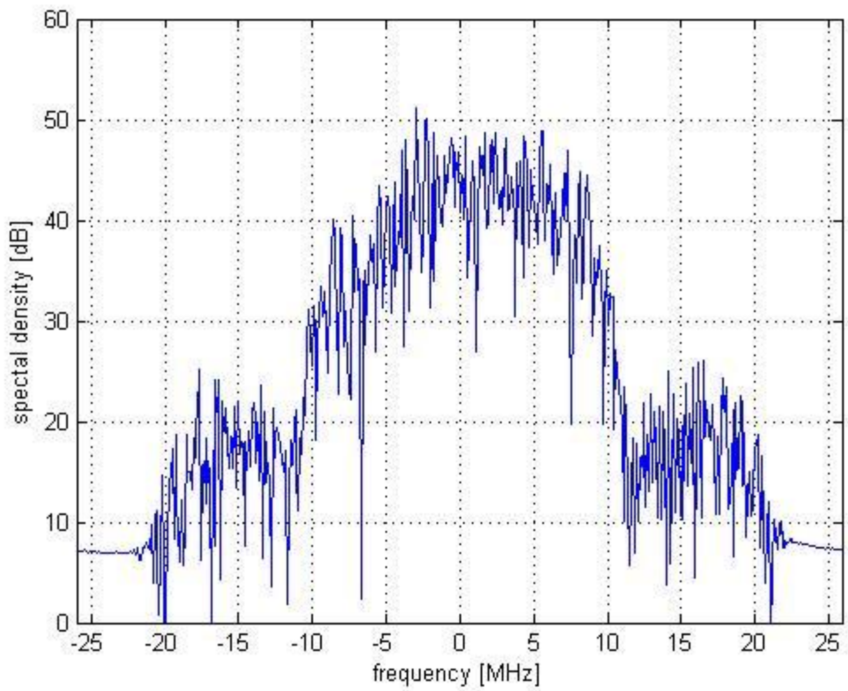

Figure 2.7 Spectrum analyzer display of a Direct Sequence (DS) Spread Spectrum signal.

2.4.2 Frequency Hopping Spread Spectrum (FH-SS)

Frequency hopping spread spectrum uses a set of narrowband channels to transmit data through all of them in a predefined sequence. It does just what its name implies. That is, it "hops" from frequency to frequency over a wide bandwidth. The specific order in which frequencies are occupied is a function of a code sequence, and the rate of hopping from one frequency to another is a function of the information rate. The transmitted spectrum of a frequency hopping signal is quite different from that of a spectrum for a DS-SS signal. The bandwidth of a frequency hopping spread spectrum signal is simply *w* times the number of frequency slots available, where *w* is the bandwidth of each hop channel. Figure 2.8 illustrates the transmitted signal frequency spectrum of an FH-SS signal.

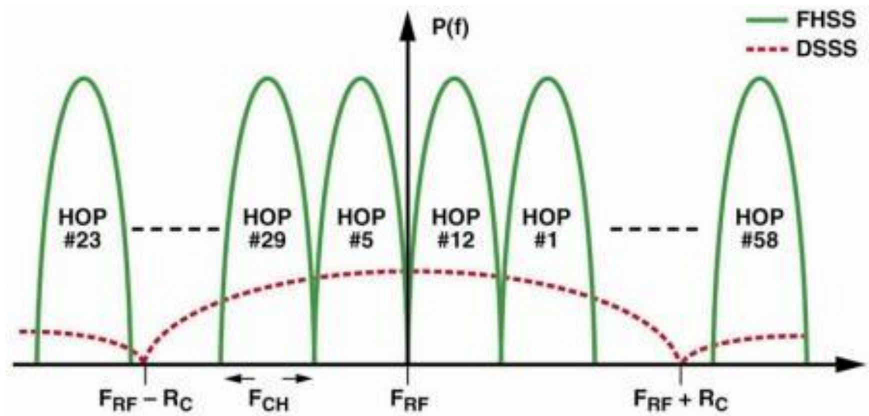

Figure 2.8 Spectrum of a Frequency Hopping (FH) Spread Spectrum signal.

The system avoids interferences by never operating on the same channel for a significant amount of time. If a channel is so bad that the system cannot use it, it just waits for the next good channel.

2.5 Error Reduction Techniques

Transmission errors in a digital communications system can be reduced by the use of two main techniques:

Automatic Repeat Request (ARQ) and Forward Error Correction (FEC)

In an ARQ system, when an error in a block of data is detected by the receiver circuit, it requests that the data block should be retransmitted. In an FEC system, the transmitted data is encoded so that the receiver can detect as well as correct errors. FEC techniques are used to correct errors on simplex (one-way) channels where returning an ACK/NAC indicator is not feasible.

The choice between using the ARQ or the FEC technique depends on the particular application. ARQ is often used in computer communication system because it is relatively inexpensive to implement, and there is usually a full-duplex (two-way) channel so that the receiving end can either transmit back an acknowledgement (ACK) for correctly received data, or a request for retransmission (NAC) when there is an error in received data. FEC is preferred in systems with large transmission delays because if the ARQ were used, the effective data rate would be small and the transmitter would have long idle periods while waiting for the ACK/NAC indicator.

2.6 Medium Access Methods

As all the devices on a communication network share the same physical medium, techniques are required in order to prevent different devices from transmitting at the same time. These techniques are collectively known as the Medium Access methods. Based on [23], this section describes three Medium Access methods: Polling, Contention and Token Passing.

2.6.1 Polling

In a polling system, one device works as the network master and all other devices function as slaves to this master. The master queries each device in turn as to whether it has any data to transmit. If the answer is yes, the device is permitted to transmit data. If, however, the answer is no, then the master moves on and asks or polls the next slave device.

2.6.2 Contention

Contention is the opposite of polling. In a contention system if one device has to transmit, it does so. The latest generation of contention based medium access methods is called as Carrier Sense Multiple Access with Collision Detection or Collision Avoidance (CSMA/CD or CSMA/CA). Under CSMA/CD when a station wants to transmit data, the station first listens to the medium to see if any other transmission is going on. If the medium is quiet, the station goes ahead with the transmission. If the medium is busy, the station waits for a random time and listens again. It is possible for two stations to transmit at the same time (sense the wire at the same time, conclude that the network is idle, and begin transmitting simultaneously), resulting in a collision. By using CSMA/CD the station can recognize collision and take corrective action.

2.6.3 Token Passing

Token passing uses a “token”, which is a small frame of data, to grant a device permission to transmit over the medium. Whichever station has the token can put data on the medium. When a station is done transmitting, it releases the token and the next station willing to transmit acquires the token. If polling and contention define the extremes of total control and total anarchy, the token passing medium access method exists somewhere in the middle of the spectrum.

2.7 Conclusions

This chapter presented the basic concepts of a digital communications system for data communication.

The transmission of data over electric power line presents various challenges. The terms and techniques discussed in this chapter will be used in subsequent sections in this thesis. Enabling data communication over powerlines is a careful combination of various approaches. Certain modifications and enhancements to conventional signaling techniques are used to accommodate the characteristics of the PLC communications medium.

3. Home Networking over Powerlines

In the present digital age of information technology, the demand for sending digital voice, video, and Internet data to and around a home, office or other building increases continuously. Installation of wires to support this is an expensive, disruptive and time-consuming process. In the context of a home networking environment, “no new wires” is the term applied to those technologies that utilize the existing wiring systems to distribute high-speed data and video throughout the home (or small office).

Phoneline and powerline systems are two dominant “no new wires” technologies. With the recent trend of deregulation and privatization of electric utility providers, these businesses can now be classified into three major types: power generation, transmission, and local distribution. The local distribution arena is highly competitive and presents numerous challenges and opportunities to the electric utility providers, including the provision of new services in addition to the electric power and building brand recognition. The electric utility providers can take advantage of the existing wiring infrastructure for provision of certain services. Telecommunication carriers, for example, are interested in a reliable way to move their content and services to the various devices in the home. Home networks are a way to achieve this.

3.1 Home Networking and Automation

With present broadband networks establishing new benchmarks in terms of speed and reliability, there is a rapidly growing small office home office (SOHO) networking scenario, where a consumer has two or more PCs, printers, scanners, or digital home entertainment devices. The need for enabling all these devices to communicate with each other as well as the Internet, along with the control of home appliances by the consumer are some of the driving factors demanding a home networking solution.

3.2 Home Networking Challenges

Commercial networks are being designed specifically to carry data between computers. They typically use fiber optic, twisted pair, or coaxial cables to minimize noise and interference over the communication medium on the network. Most homes today do not have dedicated high-speed network cabling installed. The labor costs associated with the installation of such dedicated cabling is very high for the homeowners to fund on their own. Home environments present some novel and unusual challenges that have not been primary concerns in network deployments until now. For home networking to be successful, solutions must exist that utilize the existing wiring infrastructures [50] [25]. Hence, the challenges for companies that are creating home networking technologies are based on the following criteria:

- Existing wiring infrastructure should be utilized by the technology
- Ease of installation and maintenance
- Ease of use and simplicity (use of existing standards and software platforms)
- Quality of service (QoS) mechanism should be included providing low latency for telephony and other voice application
- Data rates of 10 Mbps or higher should be supported to allow consumers distribute multimedia in real time
- Extensibility
- Data type versatility (audio, video, etc.)
- Should provide automatic security to protect against intrusion and leakage of data

• Technology must be relatively cheap compared to other existing solutions

There have been certain dissatisfactory approaches to home networking in the past as well. Consumers have long been promised a networked home, but only few vendors have actually attempted to provide it, and the approaches taken thus far have been either piecemeal or too complex [24]. Two PCs sharing files is not the vision of a fully networked home that consumers have been presented over the years. Nor will complicated systems requiring the consumer to be network managers will win their hearts and minds. Disagreements among vendors over interconnectivity standards have also been a roadblock to developing usable home networking solutions. Many of the forces that lead to the creating of business networks – the need to optimize the use of resources, distributed data availability, cooperation, backup, and centralized administration – are becoming requirements for the home [25]. Currently, significant problems are being addressed and will inevitably be solved. Original Equipment Manufacturers (OEM's) are providing consumers with comparatively fast technologies as well as ease of use and relatively cheaper prices as compared to other existing solutions.

3.3 Home Networking Technologies

The broad approaches to home networking can be found in [26] and are highlighted in this section. Many types of broadband home networking are now available. With each type addressing certain user needs and application requirements, none has been comprehensive enough to satisfy the need for all applications, and thus new technologies are being built constantly to better address the needs.

Broadband Home Networks (BHN) can operate over various physical media. Broadband home networks fall into three major categories: structured wiring, existing wiring, and wireless.

- Structured wiring requires the installation of new cabling in the walls. Both the cabling (typically unshielded twisted pair [UTP] or optical fiber) and its installations are defined by standards highlighted in [27].
- Existing wiring makes use of electrical, telephone, or coaxial wiring already installed in the walls.
- Wireless avoids the use of wires by transmitting data bearing signals through the air.

Table 3.1 presents comparisons of these approaches.

Differentiator	**Structured wiring**	**Existing wiring**	**Wireless**
Best uses	New construction and remodeling	Interconnecting stationary devices	Mobile devices such as laptops, palmtops and webpads
Cost	High (for installation)	Low	Low
Useful lifetime	Very long	Relatively short	Short
Number and location of 'outlets'	Wherever needed	Multiple electrical outlets in every room; many rooms with telephone outlets; few rooms with coax outlets	Ideally throughout the home
Current data rate (Mbps)	100	10-14	54
Future data rate (Mbps)	1000 or more	30-250	100 or more
Security	Highly secure	Less secure	Less secure
Standardization	Well defined global standards	Competing standards	Competing standards

Table 3.1 Comparison of broadband home networking approaches.

3.3.1 Structured Wiring Technologies

Structured wiring provides high bandwidth and excellent security. To handle the full range of current applications, a complete installation requires several cabling types, including UTP for telephone and data, and coaxial cable for video. Fast Ethernet at 100 Mbps over UTP is widely used for data applications. While having sufficient bandwidth for video, it does not currently include any form of Quality of Service (QoS) support. With the introduction of HD video to the home, it is believed that the home backbone network required will be based on structured wiring to interconnect sections of the home. The Electronic Industries Alliance (EIA) and Consumer Electronics Association (CEA) are developing the R-7.4 VHN Home Network Standard for this purpose [30].

3.3.2 Existing Wiring Technologies

As structured wiring is relatively expensive to install within an existing home, various companies are now developing technologies based on the existing wiring in the walls of the home.

Phoneline technologies use the existing telephone wiring. The Home Phone Networking Alliance (HomePNA) [28] has defined a 3.1 specification that reaches an unprecedented data rate of 320 Mbps. As the only home networking industry specification capable of reaching above 100 Mbps and with inherent deterministic Quality of Service (QoS), HomePNA technology complements wireless networking technologies providing the ideal high speed backbone for a home multimedia network requiring a fast and reliable channel to distribute multiple, feature-rich digital audio and video applications throughout a home. The International Telecommunication Union (ITU) has already approved global phoneline networking standard recommendation G.9954 based on the

HomePNA 3.1 specification. HomePNA members companies are working together to present recommendations based on version 3.1 to the ITU-T (Telecommunication Standardization Sector). A typical HomePNA network is shown in Figure 3.1.

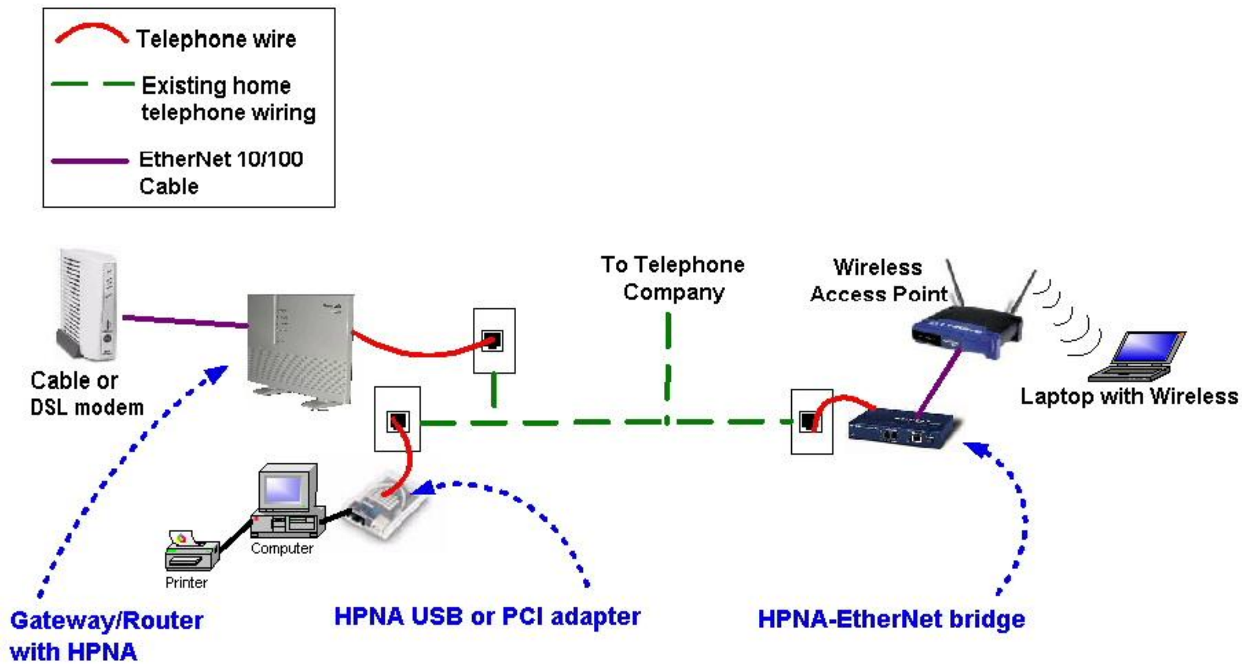

Figure 3.1 Typical HomePNA Network [Courtesy: HomePNA].

Powerline technologies use the existing electrical wiring. There are many competing technologies which are highlighted in Chapter 5. The HomePlug Powerline Alliance [29] has brought several vendors together and defined various standards for powerline. The Consumer Electronics Association (CEA) R7 Home Network Committee [30] is also working to ensure current and future Home Networks can coexist within a home and share information through the use of industry standard interfaces. Powerline networking technology will be developed further in Section 3.4.

Coax technologies use coaxial cabling as the transmission medium. A Home Cable Network Alliance (HomeCNA) [29] is working towards defining a specification.

Table 3.2 presents a comparison between the various existing wiring technologies.

	Phoneline	**Powerline**	**Coax**
Current data rate	1-10 Mbps	1-14Mbps	TBD
Future data rate	30-100 Mbps	30-250 Mbps	TBD
QoS support	Yes	Yes	TBD
Standardization	Stable	Influx~Stable	In flux

Table 3.2 Home networking technologies using existing wiring.

3.3.3 Wireless Networking

Wireless Local Area Networking (WLAN) started as a wireless extension to the enterprise LAN networks. WLAN has recently affected a breakthrough from its original application towards home and public space, appearing as a disruptive technology due to its undisputed cost-to-performance ratio. Wireless networking avoids the cost of pulling new wires and the challenges of using existing wiring.

There are many competing technologies and associated standards and advocacy groups in the area of wireless networking. Several specific implementation strategies are presented below.

IEEE 802.11 [32] is a family of evolving standards, originally designed for enterprise networking and now moving into the home networking market. The 802.11b/g scheme operating at 2.4 GHz is currently the most widely used version. The 802.11n scheme operating at 2.4/5GHz is expected to take over the current versions in the future.

HomeRF [33] was a family of wireless LAN technologies specifically designed for the home. HomeRF allowed both traditional telephone signals and data signals to be exchanged over the same wireless network. Therefore, in HomeRF, cordless telephones and laptops, for example, could share the same bandwidth in the same home or office. With the incompatibility with 802.11b, the HomeRF working group seemed to favor 802.11a in the next generation. The HomeRF Working Group was disbanded in January 2003.

Bluetooth [34] [35] short-range radio technology, developed by Ericsson and others, makes it possible to transmit signals over short distances between phones, computers and other devices. Bluetooth was designed for short-range personal networking and is being extended for longer ranges.

HiperLAN [36] is a family of European Telecommunications Standards Institute (ETSI) standards for wireless LANs. The standards are similar to IEEE 802.11 family, but also include QoS and support asynchronous transfer mode (ATM) as well as Ethernet.

Ultra Wideband [37] is based on the low-power spread spectrum data transmission technique. Table 3.3 summarizes the above mentioned wireless access technologies. The information presented in Table 3.3 is taken from [26].

	IEEE 802.11	**HomeRF**	**Bluetooth**	**HiperLAN**	**Ultra Wideband**
Frequency spectrum	2.4/5 GHz	2.4GHz	2.4 GHz	2.4/5 GHz	3-6 GHz
Current data rate (Mbps)	54	About 10	About 1	About 10	NA
Future data rate (Mbps)	Around 100 or more	NA	TBD	54	100
QoS support	No; planned for future	Yes	Yes	Yes	Planned

Table 3.3 Wireless home networking technologies.

3.4 Powerline Networking

In the powerline carrier (PLC) communication systems, the powerline is used not only for energy transmission, but also is used as a medium for data communication. Powerline networking is an emerging home networking technology that allows the end-users to use their already existing electrical wiring systems to connect home appliances to each other and to the Internet. Home networks utilizing the high-speed powerline networking technology are able to control anything, which plugs into the AC outlet. This includes lights, television, thermostats, and alarms among others.

Powerline communications fall into two broad distinct categories: access [50] and in-house. Figure 3.2 illustrates the various components of powerline networks.

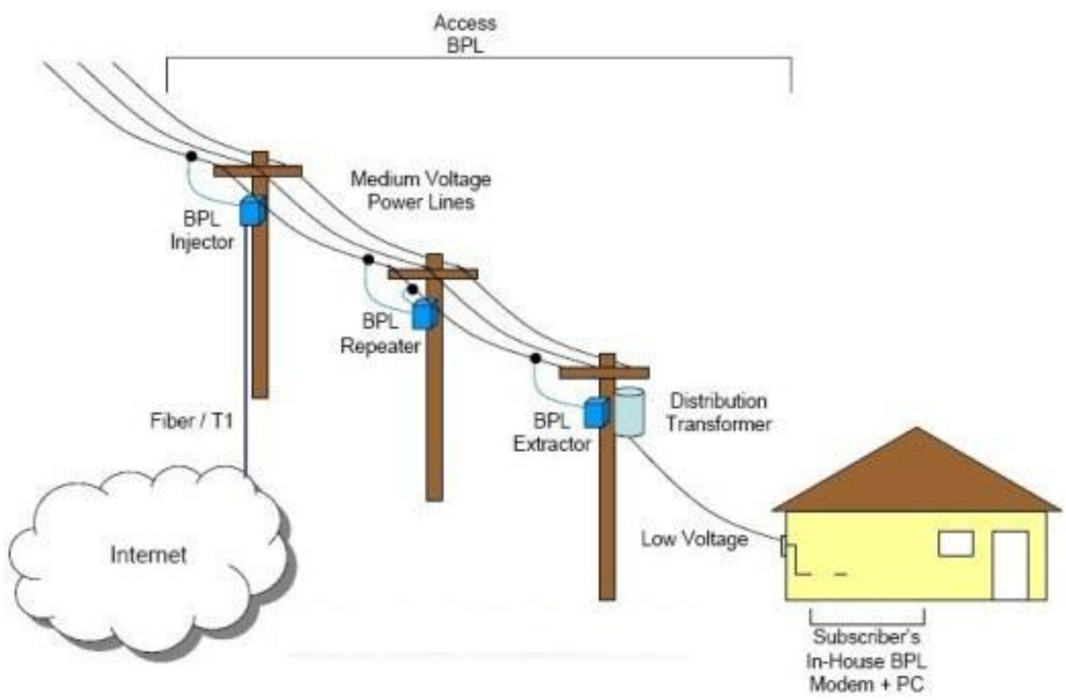

Figure 3.2 Configuration of powerline networks [77].

3.4.1 In-House and Access Powerline Technologies

The **access** powerline systems utilize three components of the electric power distribution network. The first is the medium voltage line, carrying typically 1000 to 40,000 volts, over which an electric utility brings power from a substation to a residential neighborhood. The second component is the bypass of the low-voltage transformer in the residential neighborhood that steps down the line voltage to the 220/110 volts needed for residential use. The third component of the existing power distribution system is the low voltage distribution from the transformer to residential electrical outlets, including the exterior service cable, circuit breaker panel, and interior wiring. **Access** powerline technologies (or Access broadband over powerline (Access BPL)) are responsible for sending high-speed data and voice signals outdoors over the medium voltage powerline from a point where there is a connection to a telecommunications network. This point of connection may be at a power substation or at an intermediate point between substations, depending on the network topology. Near the distribution point to a residential neighborhood, a coupler or bridge circuit module is installed to enable the transfer of high-frequency digital signals across the low voltage distribution transformer. The reason for using a coupler or bridge circuit is that the low voltage transformer, which is intended to conduct 60 Hz power signals, is a poor conduit for high-frequency digital signals. The advantages of this transformer bypass path are its low cost and ease of instillation and maintenance, Also, the bypass will not degrade the overall reliability of the electrical distribution system. The transformer bypass path, as shown in Figure 3.3, is composed of an MV inductive coupler, a transformer X-node, and an LV coupler. Finally, the high-speed communication signals are brought to the home over the exterior service power cable from the bridge across the distribution transformer, either directly, or via an access powerline adaptor module.

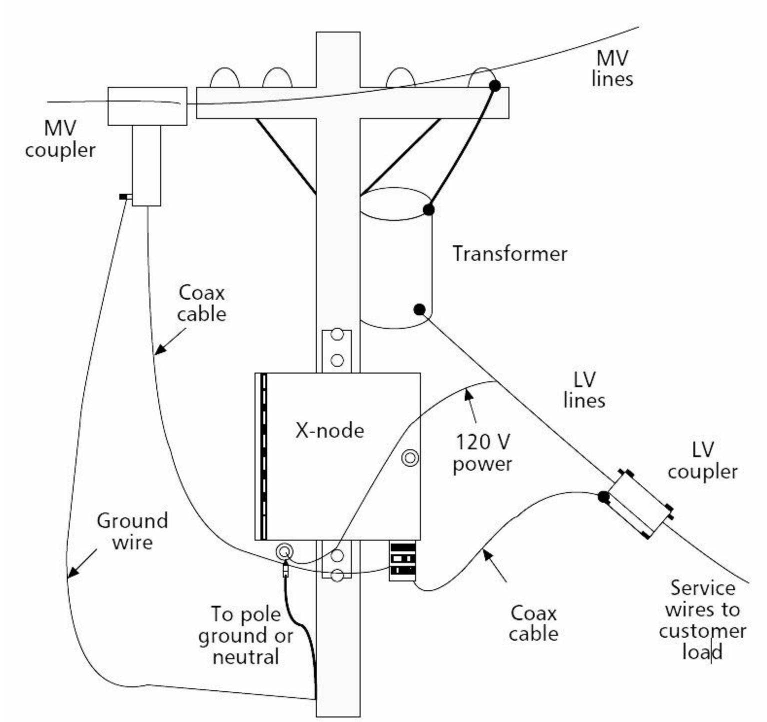

Figure 3.3 Transformer bypass path [8].

The powerline access technologies enable a "last mile" local loop solution which provides individual homes with the broadband connectivity to the Internet. Several consortiums have been organized to promote Access BPL and its applications. However, the operating characteristics of Access BPL are not standardized.

In-house (sometimes also termed as in-home) powerline technologies communicate data exclusively within the consumer's premises and extends to all of the electrical outlets within the home. The same electrical outlets which provide AC power are acting as access points for the network devices.

The access and in-house powerline networking solutions both send data signals over the powerline. However, the technologies differ fundamentally. The focus of access technologies is on delivering a long-distance solution, competing with xDSL and broadband cable technologies. The in-house technologies focus on delivering a short-distance high-bandwidth solution (≥10 Mbps) that competes with other existing in-home interconnection technologies like phoneline, cable and wireless [50].

The *access, or medium voltage* (MV), powerline technology is capable of providing broadband data transmission and provides that extra link where the telecommunication network does not reach without expensive infrastructure extensions. Broadband powerline communication systems are now commercially available. They provide data transmission over the Low Voltage power grid from the Low Voltage transformer station to the household power socket. Connection to the telecommunication network presently requires a direct connection via fiber, copper wire pairs or wireless. An example of access powerline networks is the “ABB Medium Voltage Powerline Solution” [16] that provides cost effective broadband data transmission over the existing Medium Voltage power line and brings a significant improvement in the infrastructure costs of powerline communication projects. The ABB system, certified for use up to 24 kV, provides data transfer rates of up to 10 Mbps and is based on well-tested components. Powerline communication provides power grid owners with new business opportunities. The Medium Voltage powerline communication solution, combined with Low Voltage powerline to the home allows the power utility to offer cost-effective, wide-coverage, broadband data services. The Medium Voltage powerline solution closes the gap between the Low Voltage network and the telecommunication network. Figure 3.4 shows a powerline access technology network.

In the *in-house,* or *low voltage* (LV), powerline technology in order to support the data transmission over the power grid, a Powerline Carrier Controller (PLC Controller) is installed, typically in the local transformer. The PLC Controller is coupled upstream to the telecommunication network, either via traditional methods, or using some innovative/proprietary solution from the energy provider (for example, the ABB Medium Voltage Powerline Solution). Downstream, the PLC Controller handles the data transmission (Internet and Voice) over the existing low voltage network to the home and the inhouse low voltage network. Connecting the PC or other household devices to the network can be done simply by plugging a powerline module/modem into the household power socket. Using powerline modules at home or in the office provides network facilities for PCs and printers just by plugging into the in-house low voltage network. Direct connection of a telephone to the powerline modem provides voice connection. The low voltage in-house network is easily transformed into a local telephone network simply by using a number of powerline modems plugged into power sockets as needed [74]. Figure 3.5 illustrates the versatility in connecting devices to a network via PLC techniques.

3.4.2 Components of an In-House Powerline Network

A typical in-house powerline network is illustrated in Figure 3.6 that consists of the following elements:

- House wiring inside of the building
- Appliance wiring (power cords)
- The appliances themselves (load devices)
- The electric meter (circuit breaker)
- Powerline networking modules (modems, bridges, routers, etc.)

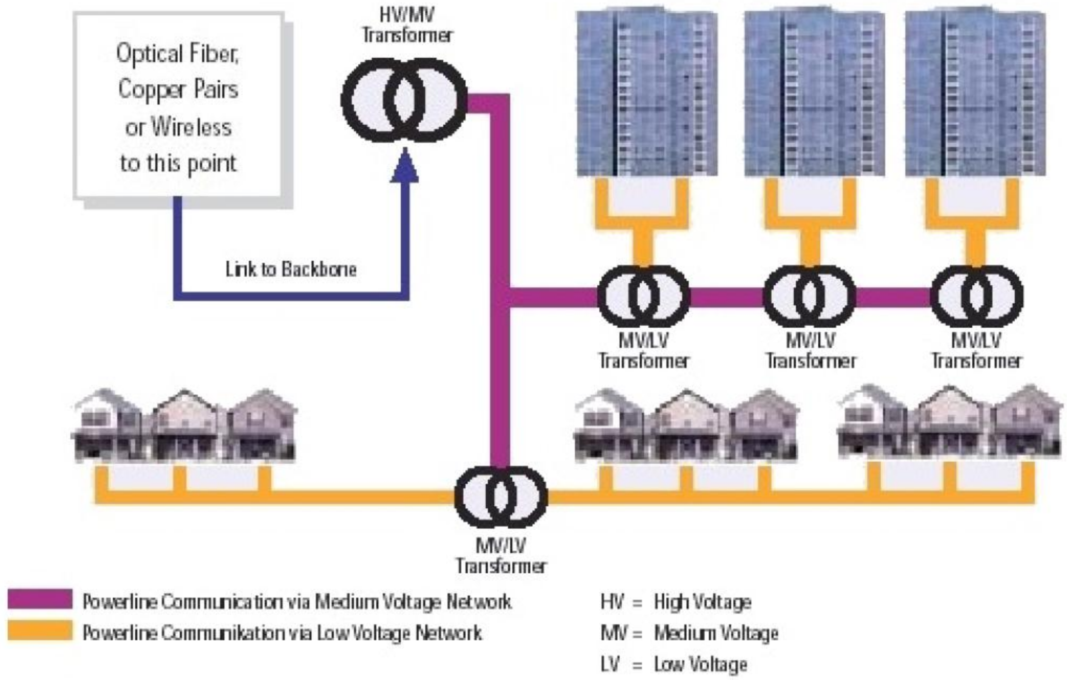

Figure 3.4 Powerline Access Technology (MV) Network [Courtesy: ABB].

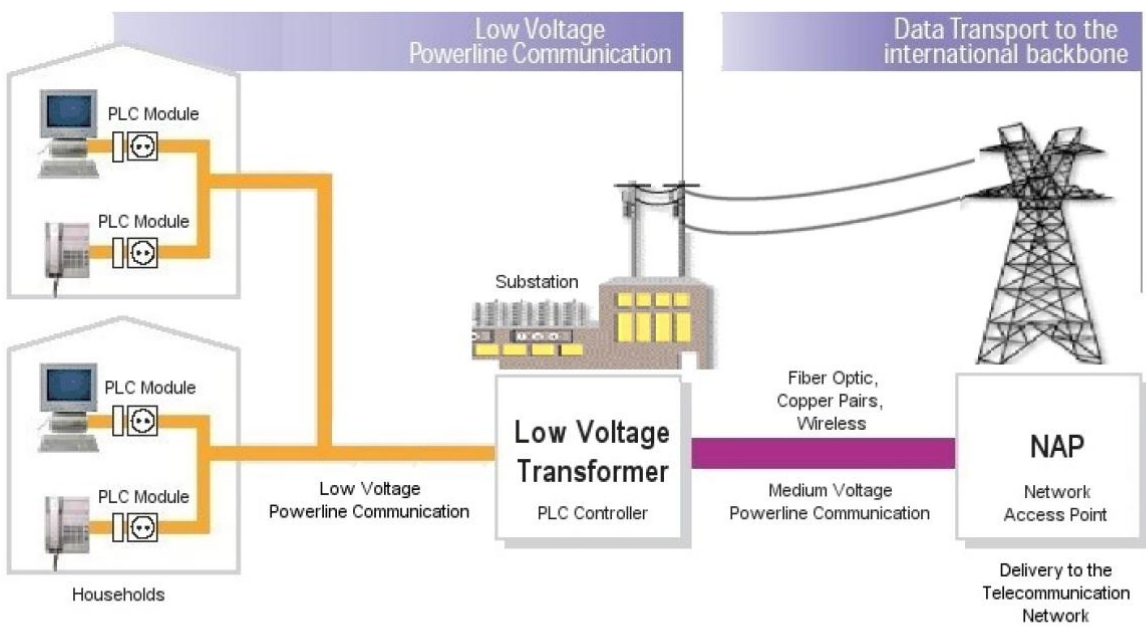

Figure 3.5 Powerline In-House Technology (LV) Network [Courtesy: ABB] [74].

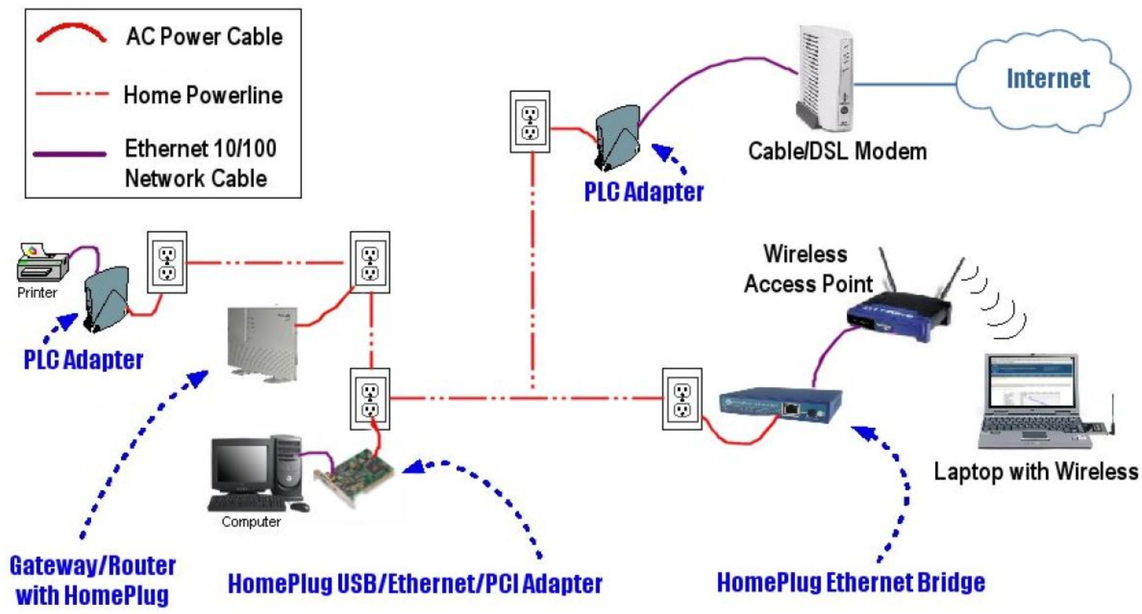

Figure 3.6 A typical in-house powerline networking scenario [28].

3.4.3 Advantages of In-House Powerline Networking

This section highlights the advantages of using the powerline as the transmission medium for in-home networking.

Ubiquity of electrical outlets: The main advantage of using the powerline infrastructure for home networking is the availability of multiple power outlets in every room. Thus, the “no new wiring” concept eliminates the need to do additional wiring (or rewiring) within the home.

Data transmission capability: Powerline networking takes advantage of the unused capacity of the power cable to transmit data over the existing home electrical power cabling.

Distribution of multimedia: Powerline networking is capable of distributing audio, video, and other real time services alongside data, throughout the home.

Speed: With the technological advancements, powerline networking is capable of distributing data at 40Mbps to 80 Mbps speed and future data transmission rates include 300 Mbps, making it an advancing technology with a future.

3.4.4 Disadvantages of In-House Powerline Networking

This section highlights some of the major disadvantages associated with In-house powerline networks.

Noise: The relatively large amount of electrical noise on the electrical powerlines limits practical data transmission speeds to somewhat lower values than normal.

Noise Sources: Vacuum cleaners, light dimmers, electric lamps, kitchen appliances, and electric drills are examples of noise generating sources that affect the performance of a powerline-based home network.

Minimum Security levels: HomePlug certified products have a built-in 56-bit DES encryption, however it is not turned on by default. Thus, powerline communication channels do not necessarily provide a secure media.

Data attenuation: Presence of various elements on the powerline network makes data attenuation a considerable issue in powerline networking.

High costs of residential appliances: In comparison to the phoneline network equipment, the powerline networking modules are more costly. The cost issue needs to be addressed so as to make powerline communication a preferred technology for home networking.

Lack of standardization: Regularity issues in some international markets are also preventing the development of global standard for distributing data over existing in-house powerline systems.

3.4.5 Technical Obstacles of an In-House Powerline Network

The powerline network is prone to various technical obstacles when it comes to transferring data at considerable speeds. The typical data and communication networks (like corporate LANs) use dedicated wiring to interconnect devices. But powerline networks, from their inception, were never intended for transmitting data. Instead, the networks were optimized to efficiently distribute power to the electrical outlets throughout a building at frequencies typically between 50-60 Hz [50]. Thus, all the original designs of electrical networks never really considered using the powerline medium for communicating data signals at other frequencies.

Due to this reason, the powerline is a more difficult communications medium than other types of isolated wiring (like for example, the Category 5 cabling used in Ethernet data networks). The physical topology of the electrical network, the physical properties of the electrical cabling, the appliances connected, and the behavioral characteristics of the electric current itself all combine to create technical obstacles associated with a powerline network that is to be used for high-speed data transmission.

3.5 Typical Applications of Home Networking

The typical applications of Home Networking can be broadly classified into five categories: resource sharing, communications, home control, home scheduling, and entertainment/information.

Resource Sharing

Home networking allows all users in the household to access the Internet and various applications at the same time. Additionally, files (not simply data, but also audio and video depending on the speed of the network) can be swapped, and peripherals such as printers and scanners can be shared. Furthermore, the need for having more than one Internet access point, printer, scanner, and/or software packages in a home/private networking scenario is eliminated. Home networking technologies can successfully be used to distribute IP-based data across the home with considerable speeds.

Communications

Home networking allows easier and more efficient communication between users within the household and better communication management with outside communications. Phone, fax, and e-mail messages can be routed intelligently in a home network. Access to the Internet can be attained at multiple places in the home with the use of terminals and Webpads, etc.

Home Control and Automation Systems

Home networking can allow controls within the house, such as temperature and lighting, to be managed through the network and even remotely through the Internet. The network can also be used for home security monitoring with network cameras.

Powerlines have been used for home automation for many years. The most important types of home automation applications include controlling lights, ventilators, security systems, sprinklers, and temperature levels within the home. The home control networking systems market is undergoing a significant transition from closed-loop solutions to open, IP-aware solutions. Home control and automation systems are normally based on one of the three major powerline technologies namely, CEBus, LonWorks, or X-10. These technologies are discussed in depth in later sections of this thesis.

Home Scheduling

A home network would allow families to keep one master schedule that could be updated from different access points within the house and remotely through the Internet.

Entertainment and Provision of Information

Home networks enable a plethora of options for sharing entertainment and information in the home.

Networked multi-user games can be played as well as PC-hosted television games. Digital video networking will allow households to route the video from direct-broadcast satellite (DBS) and DVDs to different set-top boxes, PCs, and other visual display devices in the home. Streaming media such as Internet radio broadcasts can be sent to stereo systems located within the home as well as PCs for archiving purpose.

Table 3.4 lists some of the home networking applications, what they can do for the consumer, how they are delivered, and their level of availability [24]. Some of these are based on future scenarios, and some have been delayed because of the slowdown in current economic sector related to the IT industry.

Application	Activity	Products	Delivery Time
Entertainment (Video, Audio, Music)	● Distribute multimedia content throughout the home ● Video and music on demand	● TV receivers, displays, DVDs, cable satellite receivers, MP3s, personal video recorders ●Various set-top boxes, desktop, and handheld display devices	Available
Information News, business, sports Calendar listings	● Personalized newscasts, customized business and sports data ● Event listings targeted to personal agenda	PCs, set-top boxes, handheld devices	Available
Education	Home education, enrichment, homework, training, online seminars	TVs, set-top boxes, PCs, phones, software	● Limited use today ● Growing acceptance during present decade
Telecommuting	Self-employed or remote access to corporate network	PCs, phones, display devices, software	Available
Communications	● Voice and video communications ● Live conversations and stored messaging services ● Internet access	● Phones (wired, mobile, cordless) ● Video cameras ● Display devices ● Modems, set-top boxes, wireless access devices	● Available ● Expanded services coming
Financial Services	Banking and Investment	PCs, handheld devices	● Limited ● Growing acceptance during present decade
Productivity (Coordinate family events)	● PC-shared peripherals and software ● Shared Internet access ● Calendar software	● PCs, printers, modems, scanners ● Software ● ASP connections	● Small reach presently ● Widespread;
Home Management (Power Controls)	Energy conservation Remote power management	● Major and small appliances ● Central heating/air conditioning	● Limited ● Widespread
Security	Monitoring of household and individual homes	Surveillance Cameras, monitors, telecom connections	● Available ● Widespread

Table 3.4 Home Networking Applications.

3.6 Conclusions

This chapter presented the various existing home networking technologies highlighting the advantages and salient features associated with each technology. The choice of a suitable home networking and automation technology is a combination of several factors governing the need and requirements of the consumer. The fundamental concept of powerline networking was also presented in this chapter along with the pros and cons associated with the technology. Powerline networking offers several advantages over other available home networking technologies. Among the most significant advantages are the availability of power outlets in abundance within every home, the elimination of laying new wiring, the reliability and quality of service, and data speeds of 14 Mbps enabling delivery of information including data as well as multimedia throughout the SOHO scenario.

4. Communication over powerlines

Due to its omnipresence, the electric power distribution grid offers a tremendous potential for extended fast and reliable communication services. Currently, the exploitation has just started and still is far from complete. Various fields of applications can be envisioned, starting, for example, with simple inexpensive services embodied into household appliances, where data rates of only several kilobits per second or less are sufficient. A next level might be Internet access via the wall socket, where data transfer speed is in the lower megabit range up to high-speed networking that includes fast Internet access, voice over IP, and home entertainment (i.e., streaming audio and video at data rates in excess of 10 Mb/s). Another important field of research is the use of the medium voltage network for data communication purposes. The medium voltage network can be used as a backbone to connect the low-voltage transformer stations to the Internet if conventional backbone networks, like fiber optic cables, are missing. Clearly, the development of appropriate power line communication (PLC) systems turns out to be a severe challenge for the communications engineer, having to deal with very unusual channels that were neither designed, nor intended for signal transmission at high frequencies.

The development of power line communication systems requires detailed knowledge of the channel properties, such as transfer function, interference scenario, and channel capacity in order to choose suitable transmission methods. This chapter presents appropriate power line channel models, which form the basis for the design of a channel emulator. Such a device turns out to be extremely helpful for various tests and the comparison of performance of different communication systems. A basic estimation of the power line channel capacity clearly demonstrates their enormous potential for high-speed communication purposes. Eventually, an evaluation of different modulation schemes is carried to optimize PLC system design.

This chapter starts with an overview of the fundamental properties of power line channels and will successively point out recommendations for PLC system design. A well proven channel model, including the very peculiar interference scenario of typically affecting powerline networks is also presented.

4.1 Powerline Channel Model

The idea of using the electric power distribution grid for communication purposes is not new at all. For many decades power supply companies have been using their networks for data transmission. The main purposes, however, have been management, control, and supervision of power plant and distribution facility operation, tasks calling for rather low data rates in the kilobits per second range. Especially in Europe, a significant change occurred when the last telecommunication monopolies were ended in the beginning of 1998. As a result of this process the low-voltage power distribution network became very interesting. The use of this medium made it possible to compete against the former monopolists in providing data services over the so-called last mile. The ideas centered around using the cables between the transformer substation and customers as an access medium for high-speed Internet services, and exploiting intrabuilding installations as fast local area networks for various purposes. But many obstacles blocked the way to fast and easy solutions. On one hand, power lines exhibit strong branching, which considerably impairs the signal quality due to the presence of a large number of reflection points. On the other hand, the strong cross-coupling effects between the wires in a cable must be taken into account.

A typical European low-voltage access network link is depicted in Fig. 4.1. A data transmitter, which may be connected to the Internet, say, via optical fiber, is placed in the transformer substation. The power line channel can be characterized as a star-shaped bus structure with a

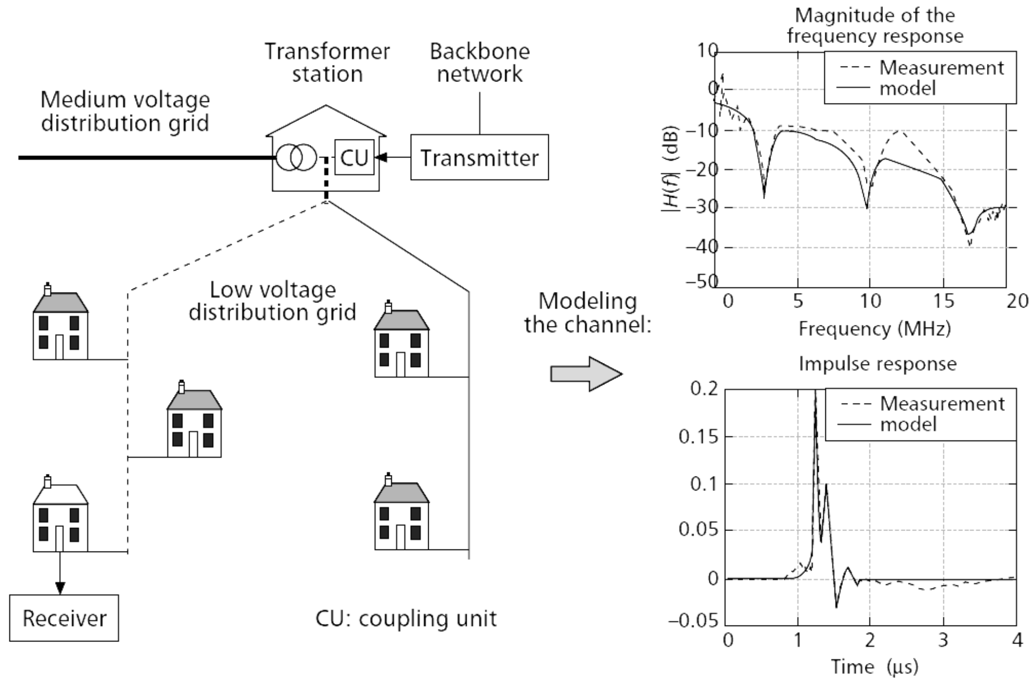

Figure 4.1 Structure of a European low-voltage access network line and associated channel characteristics [38].

branch going to each supplied building. Data receivers may be located in any of the buildings. Naturally, data transmission in the direction from the receiver to the transmitter is also possible, although not shown in the figure. Due to such a network structure, high-frequency signals suffer from various reflections. A complex echo scenario arises, leading to frequency-selective fading represented by the notches in the magnitude of the channel frequency response shown in Fig. 4.1. In addition, frequency-dependent attenuation must be considered. This effect depends on the network structure and superposes the frequency selective fading. In fact, a low- pass characteristic is commonly observed within all power line links. Therefore, the length of a link becomes crucial whenever lengths of 300 m are exceeded, whereas the particular number of 300m can vary depending on the network. In strong branched networks or for higher frequencies (i.e., above 10 MHz) this critical wire length is even smaller. In general, besides the frequency-dependent attenuation caused by the cable material, the degree of branching is responsible for increasing attenuation, as each house service point absorbs a certain amount of transmitted power.

4.2 Approaches for Modeling the Powerline Channel

Channel modeling consists of investigating the characteristics of the power network as a communication channel. PLC channels suffer from a number of technical problems, chief among them are:

- Frequency-varying and time-varying attenuations of the medium;
- Dependence of the channel model on location, network topology and connected loads;
- High interference due to noisy loads;
- High non-white background noise;
- Various forms of impulsive noise; and,
- Electromagnetic compatibility (EMC) issues that limit available transmitted power.

Two main approaches that can be utilized for modeling a powerline channel are described below.

4.2.1 Top-Down Approach

The Top-Down, or empirically based, approach is the most commonly used. This approach considers the communication channel to be a 'black box' and obtains the system parameters using experimental measurements of the powerline network. This approach describes the transfer characteristics of a channel by a transfer function. Using this approach in a multipath channel environment, the model characteristics can be established using experimental results. The major advantages of this approach are that little computation is needed and it is easy to implement. The major disadvantage stems from the fact that the channel model is vulnerable to errors in measurements.

4.2.2 Bottom-Up Approach

The Bottom-Up, or deterministically based, approach starts from the theoretical derivation of model parameters. This approach describes the behavior of a network by a large number of distributed components using matrices (scattering parameter matrices or four pole impedance and admittance matrices). Detailed knowledge of all components (cables, joints, connected devices) within a network is required for accurately setting up these matrices.

Developing a deterministic model basically means finding the transfer function theoretically without taking actual measurements of the transmission line. It is based on the intrinsic parameters (cable parameters, load impedances, etc.) of the network to establish a transfer function description of the channel.

These models generally require detailed knowledge about the components of the network to determine the elements of matrices.

The major advantage of this approach is its increased flexibility and versatility due to the fact that all the parameters of the network are formulated analytically, making it easy to predict the changes in the transfer function when a different multipath network configurations are under consideration. The major disadvantages of the Bottom-Up Approach are 1.) increased computational effort is required compared to Top-Down Approach; and, 2.) there are a large number of parameters which cannot be determined with sufficient precision.

4.3 Channel Capacity

Channel capacity is an essential feature to understand prior to designing a PLC system. Based on Shannon's theory for the capacity of Additive White Gaussian Noise (AWGN) channels, theoretical limits of data rates can be specified under the proper assumptions.

The Shannon-Hartley theorem states that considering all possible encoding techniques, the theoretical tightest upper bound on the information rate (excluding error correcting codes) of clean (or arbitrarily low bit error rate) data (meaning channel capacity C) that can be sent with a given average signal power S through an analog communication channel subject to additive white Gaussian noise of power N, is:

$$C = B\log_2\left(1+\frac{S}{N}\right), \qquad bps \tag{4.1}$$

where, C is the channel capacity in bits per second; B is the bandwidth of the channel in Hertz; S is the total received signal power over the bandwidth, measured in watts or volt^2; N is the total noise or interference power over the bandwidth, measured in watts or volt^2; and S/N is the signal-to-noise ratio (SNR) or the carrier-to-noise ratio (CNR) of the communication signal power to the Gaussian noise interference power expressed as a linear power ratio.

The use of Eqn. (4.1) is not feasible for powerline channels, since the signal-to-noise ratio is not constant within the bandwidth B, but may vary substantially. In practice, therefore, the transmitted signal power density spectrum $S_{rr}(f)$ and a frequency dependent noise power spectral density $S_{nn}(f)$ must be taken into account, so that Eqn. (4.1) has to be modified as follows [81]

$$C = \int_{f_u}^{f_0} \log_2\left(1+\frac{S_{rr}(f)}{S_{nn}(f)}\right) df, \tag{4.2}$$

Where the channel bandwidth is given as $B=f_u-f_o$.

In order to be able to use Eqn. (4.2), the transmission power density spectrum $S_{tt}(f)$, the channel transfer function H(f) as well as noise power density spectrum $S_{nn}(f)$ at the receiver should be determined. The received signal power density spectrum is then

$$S_{rr}(f) = S_{tt}(f) * |H(f)|^2 \tag{4.3}$$

$$S_{tt}(f) = \frac{E(f)^2}{K(f,d)^2 * B} \tag{4.4}$$

Where E is electric field strength, and B is available bandwidth, K(*f,d*) is decoupling factor. Now it is possible to calculate $S_{tt}(f)$, $S_{nn}(f)$, and also C as a function of the available channel bandwidth.

4.4 A Multipath Model for Powerline Channels

The powerline medium is an non-stationary transmission channel owing to the variance of impedance caused by variety of appliances that could be connected to the power outlets. The powerline channel exhibits unfavorable channel characteristics with considerable noise and high attenuations for data transmission. Because it is always time varying, the powerline can be considered a multipath channel that is caused by reflections generated at the cable branches because of impedance discontinuities resulting from various electrical loads. The impedance of powerline channels is highly varying in a range between some few ohms up to a few kilo-ohms. The impedance is mainly influenced by the characteristic impedance of the cables, the topology of that portion of the network under consideration and the nature of the connected electrical nodes.

The powerline medium as a communication channel introduces attenuation and phase shift into the transmitted signals. A powerline channel model is described to discuss the dominate features that affect the signals that are transmitted over it, namely, the attenuation and delay.

A powerline medium is characterized by impedance discontinuities. The transmitted signals are thus reflected several times resulting in a multipath transmission.The powerline channel can generally be considered as a multipath channel. The multipath nature of powerline channels arises from the presence of several branches and impedance mismatches that cause many signal reflections.

The propagation of signals over powerline introduces an attenuation, which increases with the length of the line and the frequency. In addition to the frequency dependent fading that characterizes the powerline channel, deep narrrowband notches occur in the transfer function, which may be spread over the whole frequency range. These notches are caused by multiple reflections at locations of cable equipment impedance discontinuities. The length of the impulse response and the number of the reflected energy peaks that occur can vary considerably depending on the particular powerline network environment. This frequency dependent attenuation behavior can be described using an 'echo model' for the channel behavior.

Multipath propagation approaches, which are suitable for describing the transmission behavior of power line channels, have been proposed by Philipps and Zimmermann [73][80]. Philipps's echo model describes the channel impulse response as a superposition of N Dirac pulses representing the superposition of signals from N different paths. Each of these impulses is multiplied by a complex factor ρ_i and delayed by time τ_i . The factor ρ_i represents the product of reflection and transmission factors along each echo path. This leads to the complex transfer function described by

$$H(f)=\sum_{i=1}^{N}\rho_i \cdot e^{-j2\pi f\tau_i} \tag{4.5}$$

This model allows realistic reproduction of notches that are typically present in the channel transfer function. The model is well suited to describe indoor channels where the low-pass characteristic of the channel is not relevant.

For description of channels that exhibit low-pass behavior, Zimmermann [73] has proposed an adapted echo model that contains an additional attenuation factor. This model represents the superposition of signals from N different paths, each of which is individually characterized by a weighing factor g_i and the length d_i. Furthermore, frequency-dependent attenuation is modeled by the parameters a_0, a_1, and k.

$$H(f)=\sum_{i=1}^{N}g_i \cdot e^{-(a_0+a_1 f^k)\cdot d_i} \cdot e^{-j2\pi f\frac{d_i}{v_p}}. \tag{4.6}$$

Equation (4.6) describes a universal, and practically useful, form of the complex transfer function for powerline channels. While the first exponential function describes attenuation, the second one, which includes the propagation speed v_p, represents the echo signal components.

The parameters of the multipath model can be obtained from measurements of the complex channel transfer function. The attenuation parameters a_0 (offset of attenuation), a_1 (increase of attenuation), and k (exponent of attenuation) can be obtained from the magnitude of the frequency response. To determine the path parameters d_i and g_i, the channel impulse response is necessary. The impulse response gives information about the time delay of each path, which is proportional to d_i. The weighing factors g_i can be obtained from the amplitude of each impulse. Typical values for the number of paths N are in the range from 5 to 50.

4.5 Powerline Channel Noise scenario

The interference scenario is complicated and consists of colored background noise, narrowband interference and impulsive disturbances.

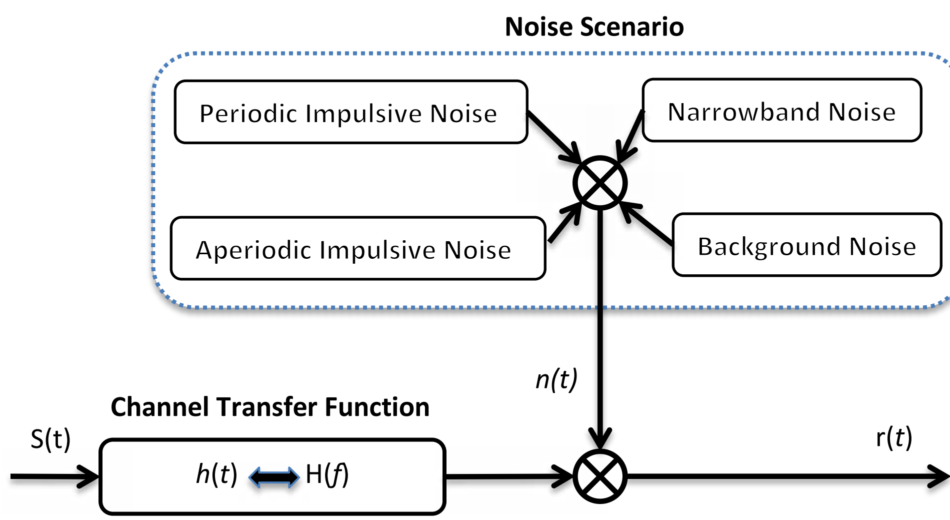

Figure 4.2 Noise processes present on powerlines.

Figure 4.2 presents an overview of the noise scenario. After passing through the PLC channel having impulse response *h(t,)* the transmitted signal *s(t)* reaches a summing node, where a variety of potential interference noise processes are added, before the signal *r(t)* arrives at the receiver. The noise various classes are now considered in greater detail.

Colored background noise is characterized by a power spectral density having a low average power level, which, however, significantly increases in magnitude within the lower frequency regime. This kind of noise can be approximated by several sources of white noise in non-overlapping frequency bands with different noise amplitudes. It is caused by common household appliances like computers, dimmers or hair dryers, which can cause disturbances within a frequency range that extends up to 30 MHz.

Narrowband interference normally consists of modulated sinusoids, the origins of which are broadcast stations present in the frequency range of 1 MHz - 22 MHz.

Impulsive noise can be classified as periodic and aperiodic. Periodic impulsive noise is further divided into interference that is either synchronous, or asynchronous with respect to the mains frequency. The synchronous portions are mainly caused by rectifiers within DC power supplies and appliances such as thyristor or triac-based light dimmers. Generally, repetition rates of multiples of the mains frequency are observed. The periodic asynchronous portions exhibit considerably higher repetition rates of 50 KHz – 200 KHz. Such interference is mainly caused by the extensive use of switching power supplies found in various household appliances today. Asynchronous impulsive noise is mainly caused by switching transients, which occur all throughout a power supply network at irregular time intervals.

4.6 Powerline Reference Channels

In order to obtain a perspective of the variety of possible PLC link properties, a selection typical, or reference channels, from an extended measurement database is presented in [38]. The database mentioned in [38] contains measurements of typical European three-phase underground distribution grids using PVC isolated cables. From the database of measurements, four channels are selected to be reference channels for a variety of PLC channel characteristics. The four reference channels are depicted in Fig. 4.3.

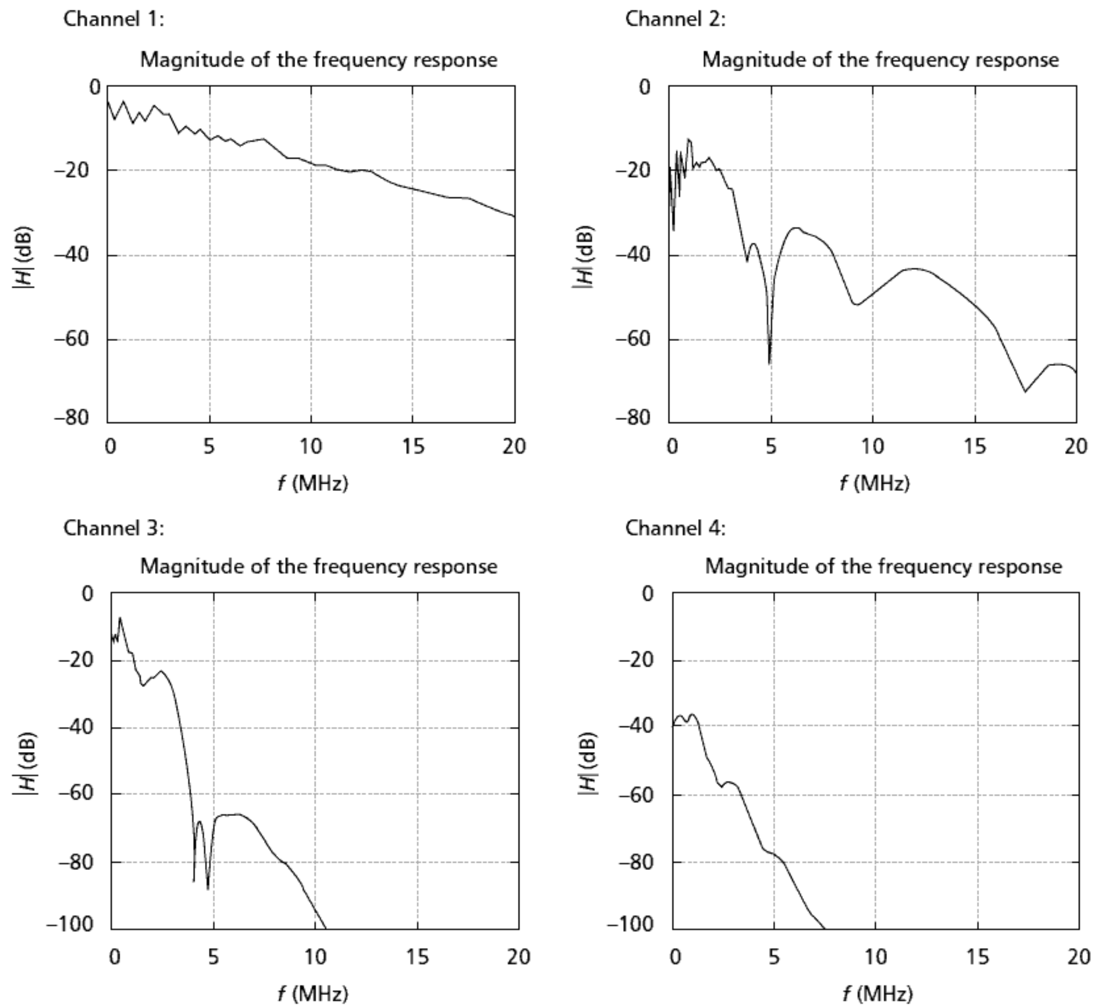

Figure 4.3 Magnitude of the frequency responses for four reference channels [38].

The channel capacity for this particular set of four PLC channels can be calculated. For example, according to a procedure proposed in [39]:

- Reference Channel 1: “excellent,” length ≈ 100 m, no branches
- Reference Channel 2: “good,” length ≈ 110 m, 6 branches
- Reference Channel 3: “medium,” length ≈ 210 m, 8 branches
- Reference Channel 4: “bad,” residential area without regular network structure (strong branching)

For EMC reasons restrictions on both transmission power levels and frequency band occupancy are required. Within international bodies such as the PLCforum [40], which is a leading international association that represents the interests of manufacturers, energy utilities, and research organizations active in the field of PLC, the following standards for the frequency bands have been proposed: Band A: Frequency range of 0.5–20 MHz; Band B: Frequency range of 0.5–10 MHz; Band C: Equivalent to B but excluding major broadcast and amateur radio frequencies. As already indicated, optimal distribution of transmitted signal power may lead to local power spectral densities that cause field strengths far above regulatory limits. Such limits, however, are unfortunately still under discussion. A reasonable approach uses the limits specified by national regulatory authorities. This leads to maximum power spectral density values from –79 dBV^2/Hz to –53 dBV^2/Hz, depending on details of the network structure [41]. Based on these prerequisites, estimates of the capacity for the Reference Channels [38] described above are listed in Table 4.1.

Channel no →		1		2		3		4	
Φss in dBV^2/Hz →		-53	-79	-53	-79	-53	-79	-53	-79
Frequency Band	A	453.7	284.9	272.7	114.4	92.3	6.0	45.4	9.5
	B	242.9	160.5	164.2	82.5	92.0	6.0	45.4	9.5
	C	146.4	97.6	98.7	50.2	55.5	2.6	26.9	4.8

Table 4.1 Channel capacity in megabits per second under transmission power spectral density limitations.

4.7 Modulation Schemes for PLC System Designs

As the properties of powerline channels differ considerably from other well-known channels, special care is necessary to select a modulation scheme that uses the potentially high capacity of these channels optimally and also offers a high degree of noise robustness. The selection of a modulation scheme for PLC systems must account for three major factors: The presence of noise and impulse disturbances causing a relatively low signal-to-noise ratio (SNR); The time-varying frequency-selective nature of the channel; and, Regulatory constraints with regard to electromagnetic compatibility that limit the transmitted power.

A choice should be made of either a robust solution which provides sufficient quality for a wide range of variations of the model parameters, or an adaptive solution. The problem is further complicated in the home environment by the need to make powerline-based home networking cost competitive with other wired or wireless solutions.

The following modulation schemes are basically applicable for use in powerline communication.

4.7.1 Single Carrier Modulation

Most basic modulation schemes make use of a single carrier at a frequency f_0. Information is encoded in amplitude, phase, or frequency changes of the carrier. Dependent on this rate of change, a more or less wideband signal of bandwidth B is generated around f_0. A modulation scheme can be characterized, for example, by its spectral efficiency. The spectral efficiency figure indicates the number of bits per second the scheme can encode into a 1 Hz bandwidth. Due to limited spectral resources, PLC technology must always aim at maximum spectral efficiency. Unfortunately, basic single carrier modulation cannot offer more than 1 bits/sec/Hz. Moreover, implementing high data rates results in the generation of contiguous wideband transmission signals, generally centered around the carrier. Due to notches in the channel frequency response and the low-pass character of the channel, such signals are seriously affected. Hence, only relatively poor performance can usually be achieved. Since the powerline channel introduces strong intersymbol interference (ISI), powerful detection and equalization techniques are needed to mitigate the effects of ISI. Thus, the advantage of simplicity in the implementation of single carrier modulation is no longer valid. However, single carrier modulation is used in applications such as In-vehicle networks. A controller area network (CAN) – based powerline transceiver is described in [46] and [47] that supports single carrier modulation, as well as baseband ASK modulation achieving bit rates up to 250 kbps.

4.7.2 Spread Spectrum Techniques

Bandwidth spreading modulation techniques were originally developed solely for military communication purposes, in order to obtain robustness against intentional disturbers and eavesdropping. In the past, the technology was characterized as requiring complex implementation and considerable costs. The rapid development of integrated-circuit complexity, however, has made spread spectrum technique (SST) available for almost any application.

Spread spectrum techniques seem to be a good choice for PLC systems due to their immunity against frequency selective attenuation and all kinds of narrowband interference. An additional interesting feature of SST, especially with regard to EMC, is the lower power spectral density of the transmitted signals as compared to single-carrier modulation schemes.

Spread spectrum techniques cope with frequency-selective channels by using a code sequence that spreads narrowband signals over a wider bandwidth. One such technique is direct sequence spread spectrum (DS-SS). Its application to wireless channels takes advantage of its robustness to narrowband interference and its low powersignal density spectrum. The latter feature is particularly attractive because several regulatory issues limit the transmitted power of powerline modems.

To take full advantage of the interference suppression of SST, a sizable bandwidth expansion is needed, which may severely limit the maximum data rate for a given transmission bandwidth. Moreover, channel equalization is needed. On the other hand, SST lends itself to multiple access techniques such as code division multiple access (CDMA), which allows several users, possibly with different rate demands, to access and utilize the PLC channel simultaneously.

A particular feature of CDMA is multiple access without the need for global coordination or synchronization. As illustrated in Figure 4.4, a single carrier is used within a communication cell, and an individual spreading code $p_i(t)$ is assigned to each participant. Each spreading code is orthogonal to the codes assigned to all other users. First, the message signal $s_t(t)$ is conventionally modulated on to a carrier having frequency f_0. In this way a spectrum $S_k(f)$ of approximately double the bandwidth of the message signal is produced around f_0. In a subsequent modulator (multiplier) fast $0/180^0$ phase hops are inserted, according to the binary pseudonoise sequence $p_1(t)$. This produces a transmission signal exhibiting a bandwidth that corresponds approximately to twice the clock frequency of the pseudonoise sequence.

At the receiver the same sequence $p(t-\tau)$ must be available, synchronized to the received signal, i.e., delayed by the signal propagation time τ between transmitter and receiver. In a first mixer the rapid phase hops are then removed and the spectrum $S_k(f)$ is restored; a conventional demodulation follows for recovery of the message. Another participant, to whom the orthogonal spreading code $p_2(t)$ has been assigned, cannot perform the mentioned spectral compression, i.e., the received spectrum $S_R(f)$ remains almost unchanged (shaded box in the lower part of Fig. 4.4). If a narrowband interferer, e.g., in the form of a broadcast radio station, appears at the input to the receiver, then it is subjected to the spreading process, so that only a small portion corresponding to the message bandwidth $S_k(f)$ can impair recovery of the desired signal.

CDMA assigns the entire frequency band to each participant alternatively, so that the access does not have to be coordinated. Each active participant, however, introduces some kind of background noise for all others. The more participants become active, the higher the probability of mutual disturbance. The situation is comparable with a room where numerous people are talking to each other at the same time but in different languages. It will work well, however, only up to a certain limit. Therefore, a general adjustment of channel capacity and the permissible number of active participants is needed. The crucial parameter in this context is the processing gain (PG), which is obtained through spreading.

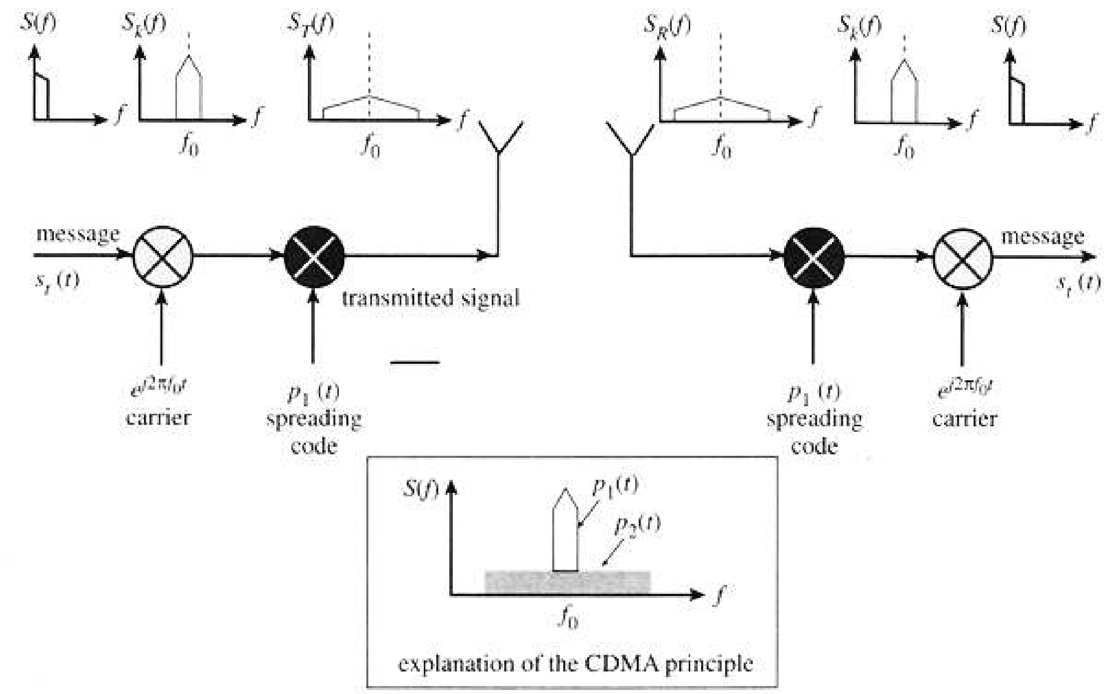

Figure 4.4 Direct Sequence Spread Spectrum transceiver and the CDMA principle [22].

If B_M is the message bandwidth after conventional modulation (spectrum $S_k(f)$ in Fig 4.4) and B_{SP} is the bandwidth of the transmitted signal (spectrum $S_T(f)$), then

$$PG = \frac{B_{SP}}{B_N}. \tag{4.7}$$

PG should be between 10 and 100 to obtain an efficient system for practical applications. The higher PG is, the more participants can access the channel at the same time. However, as a general rule, the number of participants must always remain smaller than PG; otherwise robustness against interference is lost and the signal quality may deteriorate to an unacceptable level for all users, even without additional interference.

With PG being sufficiently high, however, each user who becomes active contributes only a small amount of interference as seen by other users communicating at the same time on the channel. This particular feature of a properly designed CDMA system is also denoted “graceful degradation”. This feature of CDMA has been applied to the American mobile phone standard IS-95 and for Universal Mobile Telecommunication System (UMTS). Unfortunately, the main advantages of CDMA cannot be exploited for PLC for various reasons, including the lack of large contiguous spectrum portions. The resulting fissured spectrum is bad for CDMA. However, an application of spread spectrum technology using the DS-CDMA technique has been proposed which is effective in improving the noise-resisting ability of the communication system [82]. The method also solved the major problem encountered in PLC systems of security by using random pseudo noise. It has also been noted in [82] that decreasing of the spread spectrum carrier frequency band and amplification of the transmission power can effectively counter line attenuation.

Apart from CDMA, two further aspects must also be mentioned which will rule out most kinds of wideband single-carrier schemes for use in PLC systems:

- Single-carrier broadband schemes do not exhibit high spectral efficiency; i.e., the transmission of a digital data stream with the symbol rate r_s requires a bandwidth of at least $2r_s$, which means that the following total bandwidth must be available for N users

$$B_{SP} > 2 \cdot N \cdot r_s \tag{4.8}$$

- The powerline channel does not provide flat transmission characteristics over large bandwidths within the available spectrum. The channel generally exhibits lowpass and strong frequency-selective fading effects.

The second statement means that rather complex equalization would be required at the receiver. Clear disadvantages for single-carrier schemes may arise under the following circumstances:

- Poor transmission characteristics possessed by the powerline channel
- Interference scenario, in particular when considering all kinds of impulsive noise
- Expected frequency allocation and transmission power level limitations

For these reasons, much attention has been focused on multicarrier techniques, in particular OFDM.

4.7.3 Orthogonal Frequency Division Multiplexing

Orthogonal Frequency Division Multiplexing (OFDM) is a well proven multicarrier technique in applications such as digital audio broadcasting (DAB), terrestrial digital video broadcasting (DVBT), and asymmetric digital subscriber line (ADSL). Similar to the bandwidth spreading modulation types, OFDM exhibits robustness against various kinds of interference and enables multiple access. In contrast to standard SST, the spectrum used by OFDM is segmented into numerous narrow subchannels. A data stream is transmitted by frequency-division multiplexing (FDM) using N orthogonal carriers, centered in the subchannels. Due to the narrowband property of each subchannel, attenuation and group delay are constant within each channel. Thus, equalization is easy and can be performed by using a one-tap technique. Orthogonality of all carriers leads to outstanding spectral efficiency, which was already identified as a key element for the success of high-speed PLC systems.

As the data stream having rate r_d is distributed to N individual carriers, a symbol rate $r_s = r_d/(m \cdot N)$ will result which is substantially slower than the data rate. Moreover, for each carrier a different modulation method dependent on the subchannel quality can be chosen. The factor m in the equation for symbol rate r_s indicates the number of bits assigned to a carrier, for example, m = 2 for quaternary phase shift keying (QPSK). Due to the increased symbol duration, transmission is much less sensitive to multipath propagation than any single carrier modulation, so equalization will not necessarily be required for OFDM. Nevertheless, the overall complexity of an OFDM system is comparable to that of single carrier solutions which include wideband equalization.

A substantial advantage of OFDM is its adaptability. As already indicated above, it is possible to choose the optimum modulation scheme individually for each subchannel. In addition, frequency ranges excluded from use for PLC due to either regulatory rules, or bad quality can easily be avoided by zeroing the corresponding carriers.

In the future it is expected that OFDM will become the most favorable modulation scheme for use in PLC systems covering a wide range of applications. Table 4.2 compares the pros and cons of OFDM with possible PLC modulation schemes that could be used in PLC systems.

4.7.3.1 Principles of OFDM transmission

The total signal bandwidth, in a classical parallel data system, can be divided into N non-overlapping frequency subchannels. Each subchannel is modulated with a separate symbol and then the N subchannels are frequency multiplexed. The general practice of avoiding spectral overlap of subchannels was applied to eliminate inter-carrier interference (ICI). This is shown in

Modulation scheme	Spectral efficiency in b/sec/Hz	Max. data rate in Mb/s	Robustness against channel distortions	Robustness against impulsive noise	Flexibility and adaptive features	System costs	EMC aspects, regulations
Spread spectrum techniques	< 0.1	~ 0.5	-	0	--	--	+
Single carrier broadband, no equalizer	1-2	< 1	--	+	--	++	--
Single-carrier broadband with equalizer	1-2	~ 2	+	+	0	-	-
Multicarrier broadband with equalizer	1-4	~ 3	+	0	0	-	0
OFDM	>> 1	> 10	++	0	++	-	+

(++ excellent; + good; 0 fair; - bad; -- very bad)

Table 4.2 A comparison of different transmission methods for powerline communication.

Figure 4.5. This practice, however, resulted in insufficient utilization of the existing spectrum. An idea was proposed in the mid-1960s to deal with this lower spectral efficiency of data transmission through the development of frequency division multiplexing (FDM) with overlapping subchannels [42]. The subchannels were arranged so that the sidebands of the individual carriers overlap without causing ICI. This principle is displayed in Figure 4.5. To achieve this, the carriers must be orthogonal. From this constraint, the idea of Orthogonal Frequency Division Multiplexing (OFDM) had originated.

Two sinusoids with arbitrary phases are said to be orthogonal when the minimum frequency

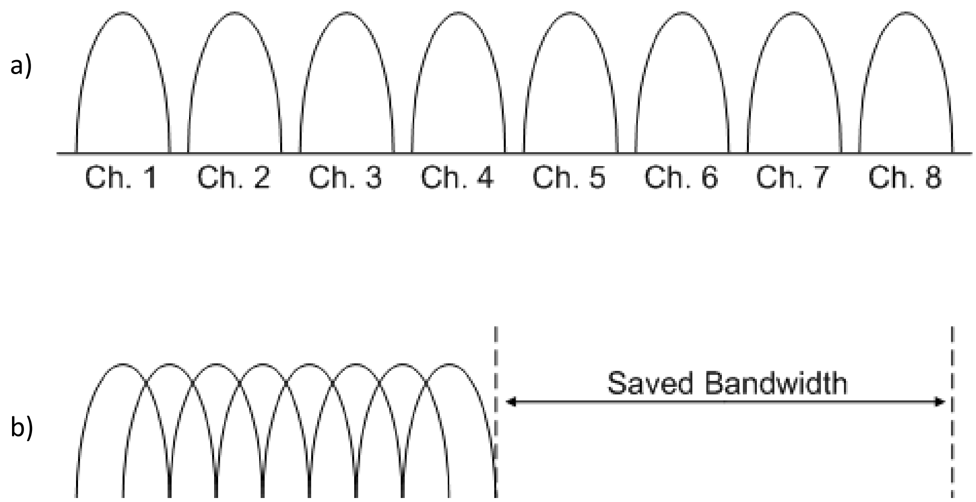

Figure 4.5: a) The frequency spectrum of eight channels shown utilizing frequency division multiplexing. Parallel transmitters are employed in which guard bands are placed between sub-carriers. b) The frequency spectrum of OFDM is shown where sub-channels are orthogonal to the adjacent channel. The percentage of bandwidth used to transmit the same data is reduced by 50%.

separation between them is 1/T, were T is the symbol period. In Orthogonal Frequency Division Multiplexing (OFDM), multiple sinusoids with frequency separation 1/T are used. The sinusoidal signals used in OFDM can be defined as

$$g_k(t) = \frac{1}{\sqrt{T}} e^{\frac{j2\pi kt}{T}} \omega(t) \tag{4.9}$$

where, k= 0,1,…,k-1 corresponds to the frequency of the sinusoidal, and (t) = u(t) - u(t-1) is a rectangular window over [0,T].

The OFDM scheme uses multiple sinusoidal signals having frequency separation 1/T where each sinusoidal signal is independently modulated by the information. The information bit a_k is multiplied by the corresponding carrier $g_k(t)$ and the sum of such modulated sinusoidal signals then forms the transmitted signal. Mathematically, the transmitted signal is described according to

$$\begin{aligned} s(t) &= a_0 g_0(t) + a_1 g_1(t) + \cdots\cdots + a_{k-1} g_{k-1}(t) \\ &= \sum_{0}^{k-1} a_k g_k(t) \\ &= \sum_{\sqrt{T}} \sum_{0}^{k-1} a_k \cdot e^{\frac{j2\pi kt}{T}} \cdot \omega(t) \end{aligned} \tag{4.10}$$

Equation (4.10) indicates that: a) Each information signal a_k multiplies the sinusoidal signal having the resulting frequency k/T, and b) All of the modulated sinusoidal signals are added and the resulting signal s(t) is transmitted over the channel.

The sampled version of Eqn. (4.10) is described by

$$s(nt) = \frac{1}{\sqrt{T}} \sum_{0}^{k-1} a_k \cdot e^{\frac{j2\pi nT}{T}} \cdot \omega(nt)\,. \tag{4.11}$$

It is observed that the above operation corresponds to an Inverse Discrete Fourier Transform (IDFT) operation.

DFT-based OFDM can be completely implemented in the digital baseband for efficient processing, eliminating bandpass filtering. All subcarriers still overlap in the frequency domain while the DFT ensures orthogonality.

4.7.3.2 OFDM System Architecture

Orthogonal Frequency Division Multiplexing (OFDM) is a signaling technique that is widely adopted in many recently standardized broadband communication systems due to its ability to cope with frequency-selective fading. It is also a candidate scheme for the proposed standard for power line communication (IEEE P1901). Figure 4.6 illustrates a block diagram for a typical OFDM system. Here c_i's are parallel substreams, s_i's are subcarriers (orthogonal), S/P is the serial-to-parallel converter, P/S is the parallel-to-serial converter, CP is the cyclic prefix, VC's are the virtual carriers, and $s_i^{(cp)}$ is the OFDM signal with cyclic prefix inserted. On the receiver side $r_i^{(cp)}$ is the received OFDM signal, r_i's are serial-to-parallel converted signals, R_i's are discrete Fourier transformed signals and c_i's are signals after channel equalization has been applied.

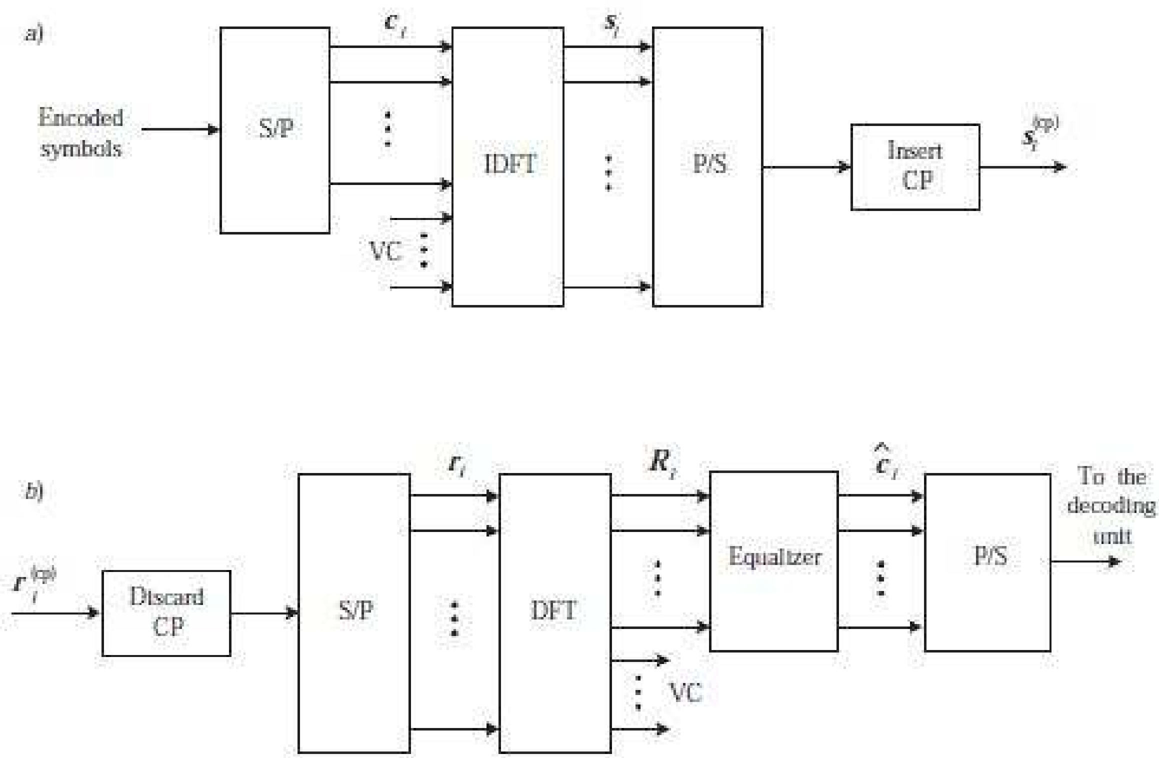

Figure 4.6 Block diagram of a typical OFDM system: a) Transmitter b) Receiver .

The main idea behind OFDM is to divide a high-rate encoded data stream into parallel substreams that are modulated onto orthogonal carriers (referred to as *subcarriers*). This operation is easily implemented in the discrete-time domain through an N-point inverse discrete Fourier transform (IDFT) unit. The IDFT takes a signal defined by frequency components and converts them to a time domain signal. The unused inputs of the IDFT are set to zero and, in consequence, they are called *virtual carriers* (VCs). In practice, VCs are employed as guard bands to prevent the transmitted power from leaking into neighboring channels. The cyclic prefix (CP) is then inserted which effectively converts the linear convolution effectively performed by channel to simulate a channel performing cyclic convolution ensuring orthogonality over a time dispersive channel and eliminating ISI completely between subcarriers as long as CP remains longer than the impulse response of the channel. However, the CP induces a loss in the effective data rate that is achievable. However, the resulting zero ICI generally compensates for the reduction. The cyclic extension is added to the data stream after the IDFT is computed. By modulating the original data onto N subcarriers, OFDM increases the symbol duration by a factor of N, thereby making the transmitted signal more robust against frequency-selective fading.

An important advantage of the OFDM transmission technique as compared to single carrier systems is seen in the context of frequency-selective channels. The orthogonality of the OFDM subcarriers is maintained after transmission over the channel and the effect of ICI is reduced to a multiplication of each subcarrier by a complex transfer factor. Therefore, equalizing the signal is very simple, whereas equalization may not be feasible in the case of conventional single carrier transmission occupying the same bandwidth. Equalization can be used to further suppress ISI and ICI. These interferences are a result of channel impulse response or timing and frequency errors such as channel distortion, synchronization error, or phase error.

Thus, OFDM is a special form of wideband multicarrier modulation in which multiple symbols are transmitted in parallel using different sub-carriers with overlapping frequency bands that are mutually orthogonal. An equivalent wideband frequency bandwidth is separated into a number of narrowband signals. The time dispersion caused by multipath delay is reduced because the symbol duration of a narrowband signal will be larger than that of a wideband transmission scheme. The overlapping multicarrier techniques can implement the same number of channels as in a conventional FDM system but with a reduced amount of bandwidth. In conventional FDM, adjacent channels are separated using a frequency guard band. In order to utilize the overlapping technique, the crosstalk between adjacent channels is reduced by maintaining orthogonality between the sub-carriers.

In OFDM, each subcarrier has an integer number of cycles within a given time interval T, and the number of cycles by which each adjacent subcarrier differs is exactly one. This implementation establishes orthogonality among the subcarriers. The subcarriers are data modulated using either phase shift keying or quadrature amplitude modulation. The amplitude spectrum of each modulated subcarrier using either PSK or QAM has a $\sin(f)/f$ shape. At the peak spectral response of each subcarrier all other subcarrier spectral responses are identically zero.

Following data modulation, symbols are fed through a serial-to-parallel conversion process. Each PSK or QAM symbol is assigned a subcarrier and an inverse DFT, contributed by Weinstein and Ebert in 1971 [43], is performed to produce a time domain signal. OFDM deals with multipath delay spread by dividing a wideband signal into N narrowband channels where N is the number of sub-carriers. However, if the delay spread is longer than the symbol duration, multipath will affect performance. A guard time is introduced to eliminate ISI caused by delay spread. As a rule, the guard time is usually two to four times larger than the expected delay spread. To reduce ICI, OFDM symbols are cyclically extended into the guard interval, as pointed out by Peled and Ruiz in [44]. This cyclic extension ensures that an OFDM symbol will have an integer number of cycles in the DFT interval as long as the delay is less than the guard time.

At the receiver after the analog-to digital conversion stage, time and frequency synchronization between the transmitter and receiver is very crucial to the performance of an OFDM link. A wide variety of techniques have been proposed for estimating and adjusting both the symbol timing and carrier frequency. To demodulate the sub-carriers using PSK or QAM modulations, an accurate reference phase and amplitude of the signal constellation on each sub-carrier are required.

4.8 Conclusions

In this section, approaches to designing a powerline communications channel have been presented. The development of a powerline communications system requires detailed knowledge of the channel properties in order to choose suitable transmission method. Appropriate powerline reference channel models have been identified which form the basis for the design of a PLC system. Furthermore, a basic estimation of the powerline channel capacity clearly demonstrates their enormous potential for high speed communication. A detailed discussion of the noise component present in a typical PLC channel had also presented.

Basic modulation techniques such as PSK and FSK can be used for low data rate communication on powerlines. Other more advanced techniques such as OFDM can be used when higher data rates are desired. OFDM was adopted by the HomePlug Powerline Alliance because of its robustness to noise, and the fact that it is a parallel data transmission method using a number of parallel frequency division multiplexed sub-bands. Since the useful bandwidth in the powerline channel is under 25 MHz, the applicability of spread spectrum modulation is considered to be limited. Using a single carrier modulation on the powerline is possible but equalizers may be needed to reduce the delay spread effect, and the associated cost is relatively high. The knowledge gained from this section has aided in the design of the PLC system for which the performance analysis is described in Chapter 6.

5. Powerline Communication Technologies

This chapter presents a review of several underlying technologies in the powerline networking arena. The technologies and standards used presently in the Powerline Communications are investigated in depth. These include LonWorks, X-10, OFDM, Passport, CEBus and the HomePlug standard. We then focus on the technologies that are being deployed based on the standards. The advantages and benefits of using powerlines as the medium for data transmission within homes are also considered along with other important factors such as the quality of service, data transmission rates, as well as various limitations of the technology. The description of present day technologies follows.

5.1 LonWorks (Local Operation Networks)

The LonWorks technology, developed by Echelon [48], and available as an open standard to all manufacturers, displaces the proprietary centralized systems with open, highly distributed, and interoperable systems for control applications. Every automatic control system (industrial or application) is comprised of the same basic components: sensors, actuators, application programs, communication networks, human-machine interfaces and network management tools. Rapid technology advancements demands changes in all types of system architectures, including those of control systems. The LonWorks technology makes possible information-based control systems, rather than the old-style command-based control systems.

Figure 5.1 shows the centralized architecture that up until recently has been typical of most control systems in commercial and industrial applications.

Typically there may be tens of thousands of sensors and actuators (I/O points) that are wired to a sub-panel, which in turn is connected to the controller panel via a proprietary master/slave communication bus. The controller panel contains a high-performance microprocessor that runs a custom application program which implements the control logic for all the I/O ports connected to it. The system may have a proprietary Human Machine Interface(HMI) with an interface to allow standard HMI tools to connect to the system [49]. The system typically resembles the legacy mainframes and minicomputer systems of past decades.

The highly distributed, peer-to-peer architecture made possible by LonWorks technology is shown in Figure 5.2. There are no centralized controllers. The LonWorks devices (also called as nodes) communicate with any other node in the system using a standard communication protocol on whatever physical medium is best (twisted pair, AC powerline, radio frequency, fiber optic cable, infrared). With each node having its own simple application program, the control logic is distributed throughout the system. Node application is customized by setting configuration parameters rather than by custom programming. Every sensor or actuator in the system can be a node. HMI and network management tools are available for different users. Each user has access to all points in the system through the common communication protocol.

LonWorks technology provides the concept of network variables (NVs), which makes it easy for manufacturers to design devices which system integrators can incorporate readily into an established interoperable, information-based control system. The benefits to the consumer (end-user or system integrator) of the LonWorks enabled flat control architecture are: compatibility, easy-to-use HMI and network-management tools reduced wiring costs, short system design cycle, reliability, multi-vendor maintenance options, and the ease of implementing new functionality.

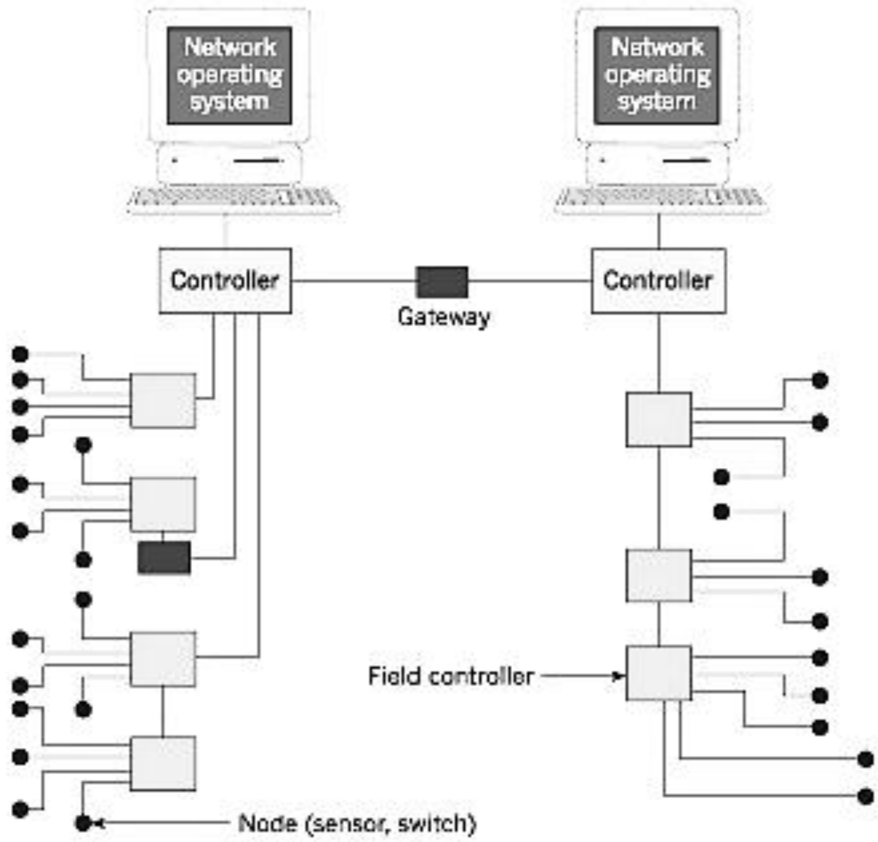

Figure 5.1 Centralized Control Architecture Model [Courtesy: Echelon] [48].

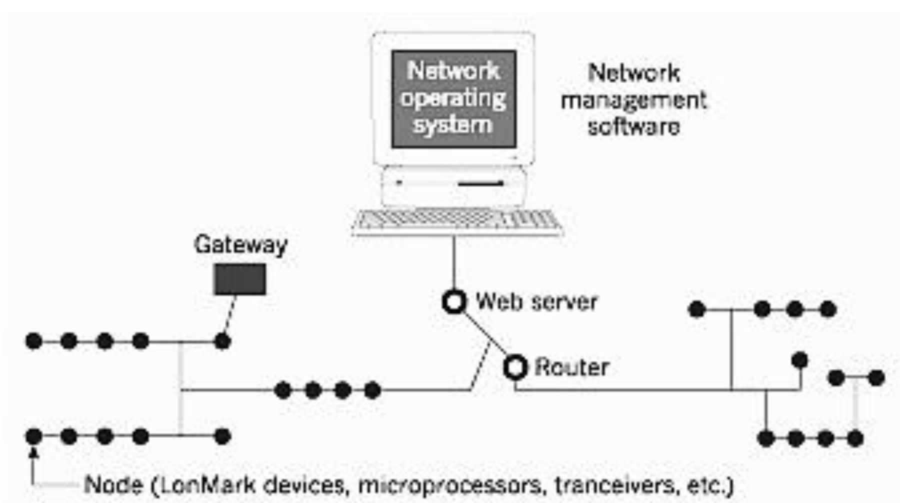

Figure 5.2 LonWorks Distributed Control Architecture [Courtesy: Echelon].

5.1.1 LonWorks Technology

This section highlights the key elements of the LonWorks technology and the components comprising the LonWorks system. A description of the salient features of LonTalk communication protocol and a discussion of the LonWorks Network Services (LNS) are also presented.

The LonWorks technology is comprised of the major elements: Neuron Chip control processors and transceivers; LonTalk communication protocol; and, LonWorks Network Services (LNS).

Neuron Chip control processor is the physical core of every LonWorks device. It is a system-on-chip with multiple microprocessors, read-write and read-only memory (RAM and ROM), communication and I/O interface ports. The ROM contains an OS, the LonTalk communication protocol and an I/O function library. The chip has non-volatile RAM for configuration data and for the application program, both of which are downloaded over the communication network. Each Neuron Chip contains a unique 48-bit code, called the Neuron ID. Available in a large family with different speeds, memory type and capacity, and interfaces, the Neuron Chips are jointly designed by Echelon and its semiconductor partners Motorola and Toshiba. A transceiver is an electronic module that provides the physical interface between the communications port of the Neuron Chip and a physical channel which transports the digital communication packets to other devices. All devices connected to a specific channel must have compatible transceivers operating at the same bit rate.

Transceivers are available from Echelon and other manufacturers for a variety of media, including single twisted pair, powerline, RF, infrared, fiber optics and coax. Bit rates depend on the media and transceiver design; a maximum of 1.25 Mbps can be achieved on a single twisted pair [49].

The Neuron Chip control processors and transceivers comprise the hardware components used in LonWorks devices, and are specifically designed to offer the most cost-effective solution available for network enabling and embedding intelligence into home control devices [50].

The LonTalk communications protocol is a layered, packet-based, serial peer-to-peer communications protocol. Adhering to the layered architectural requirements of the International Standards Organization (ISO), the LonTalk protocol is designed for the specific requirements of control systems, rather than data processing systems. Devices on a channel take turns transmitting packets. Each packet is a variable number of bytes in length and contains the application-level information together with addressing and other network information. Every device on a channel looks at every packet transmitted on the channel to determine if it is an addressee. If so, the packet is processed to determine if it contains data for the node's application program or whether it is a network management packet. The data in an application packet is provided to the application program and, if appropriate, an acknowledgement message is sent to the sending device. A network management packet is processed appropriately with no involvement required from the application protocol. The LonTalk protocol is media-independent, allowing LonWorks systems to communicate over any physical transport media. The program implementation of the protocol called LonTalk firmware is contained within ROM in every Neuron Chip; providing a number of modifiable configuration parameters to make tradeoffs in performance, security, and reliability for a particular application; a portion of non-volatile RAM in the Neuron Chip is reserved for these parameters [49]. A comprehensive summary of the LonTalk protocol is given in [68] and a very detailed bits-and-bytes level discussion is available in [51]. The LonTalk communication protocol is permanently embedded in each LonWorks device. LonTalk has been approved as an open industry standard by the American National Standards Institute (ANSI)-EIA 709.1 [50].

LonWorks Network Services (LNS) is a client-server architecture that provides the foundation for interoperable LonWorks network tools. LNS enables the component-based software design of a new generation of tools that can work together to install, maintain, monitor, and control LonWorks networks. It also makes it easy to integrate control systems with other information systems. The architecture supports clients based on any platform; servers are currently based on Windows 95, Windows NT, and the Neuron Chip. An overview of the LonWorks Network Services is presented in [52]. The LNS is the basis for easy-to-use, interoperable network management and HMI tools, and it also provides a range of network services to appliances that are connected to the control system.

5.1.2 LonWorks System Components

A typical LonWorks system consists of three types of components: LonWorks devices; Channels; and, Network tools.

Each LonWorks device, or *node*, attached to the network contains at least one Neuron Chip and one transceiver in a appropriate mechanical package, as well as a suitable power supply. Depending on device functionality, there may also be embedded sensors and actuators, I/O interfaces to external legacy sensors and actuators, or interfaces to host processors such as PC's. To accommodate complex applications, some versions of the Neuron Chips have a high-speed parallel interface allowing any microprocessor (for example, Motorola 68000 series) to execute the application program, while using the Neuron Chip, with a special microprocessor interface application, as its network communications processor. Alternatively, the open LonTalk protocol can be ported to run directly on any processor; and in that case the Neuron Chip is not required by all devices, rather all such devices are assigned a unique Neuron ID.

A *channel* is a specific physical communication medium to which a group of LonWorks devices are attached by transceivers designed specifically to operate on that channel. Each type of channel has different characteristics in terms of maximum number of attached devices, communication bit rates and physical distance limits. Table 5.1 taken from [49], summarizes the characteristics of several widely used channel types:

Channel Type	Medium	Data Rate	Max. Devices	Max. Distance
TP/XF-1250	Twisted pair, bus	1.25 Mbps	64	125 m (bus length)
TP/XF-78	Twisted pair, bus	78 kbps	64	1330 m (bus length)
TP/FT-10	Twisted pair, flexible topology	78 kbps	64 (upto 128 if link powered)	500 m (node to node)
PL-20	Power line	5 kbps	No Limit	Determined by attenuation

Table 5.1 Wireline channel characteristics [49].

A complete reference of LonMark approved channels and transceivers is found in [53]. Details on the activities and scope of the LonMark Interoperability Association can be obtained from [54]. From [49], the components of a LonWorks System are shown in Figure 5.3. The figure illustrates several categories of LonWorks devices with specific product examples. The Neuron Chips and transceivers are labeled as N and T, respectively.

The role of *LonWorks control devices* is to sense and control the state of the components that comprise the physical system being controlled. The control devices may have any combination of embedded sensors and actuators or input/output interfaces to external legacy sensors and actuators. The application program in the device may not only send and receive values over the network but may also perform data processing (e.g. scaling, linearization) of the sensed variables and control logics such as PID (Proportional Integral Derivative) loop control, data logging, and scheduling. Several control devices are shown in Figure 5.3 are described in [49] and summarized

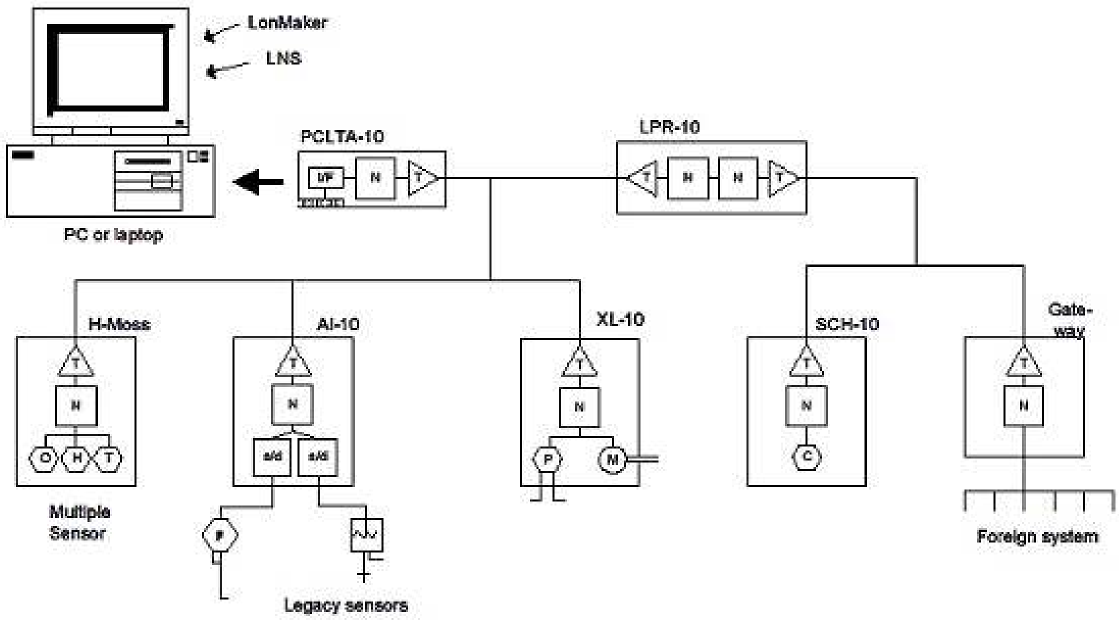

Figure 5.3 Anatomy of some LonWorks devices [Courtesy: Echelon] [48].

as follows:

- Echelon LonPoint AI-10 Module has two A/D convertors allowing up to two analog input legacy devices (4-20 ma or 0-10 volt interface) to be connected to the network.
- Hubbell H-Moss Multiple Sensor Module is a wall-mounted unit that contains three embedded sensors monitoring temperature (T), occupancy (O), and humidity (H).
- Honeywell XL-10 VAV Controller contains and embedded damper actuator motor (M) and differential air-pressure sensor (P). It obtains room temperature and setpoint values over the network and implements PID single loop control to maintain room comfort.
- Echelon LonPoint SCH-10 Scheduler module has an embedded real-time clock (C) and a highly configurable state machine logic for implementing scheduling and event-driven mode control for either all, or a portion of a LonWorks system.

5.1.3 Summary

LonWorks is an "open" technology and is accessible to all. A typical node in a LonWorks control network performs a simple task. Devices such as proximity sensors, switches, motion detectors, and sprinkler systems may all be nodes on a home network. LonWorks control networks can easily be integrated with the Internet. This built-in capability allows for seamless networking between IP-based devices and control devices. LonWorks powerline-based systems also support remote monitoring of home appliances through standard Web browsers.

5.2 Consumer Electronic Bus (CEBus)

The Consumer Electronic Bus (CEBus), is the Electronic Industry Association's (EIA) open standard (EIA-600) describing a method of communication between electronic products in the home using five different media: powerline, twisted pair, coax, broadcast RF, and infrared [55]. The CEBus is basically a local-area network for home automation. CEBus is a complete packet oriented, connectionless, peer-to-peer network utilizing Carrier Sense Multiple Access/Carrier Detect Contention Resolution (CSMA/CDCR) protocol. CEBus is a communications and product interoperability standard designed primarily for consumer products [56]. The first version of CEBus was released as IS-60 (Interim Standard 60) in 1992 for industry review, and was revised in 1993 and 1994. After that it was released as an EIA open standard (EIA-600).

The CEBus based products consist of two fundamental components: a transceiver and a microcontroller. Data packets are transmitted by the transceiver at about 10 Kbps [50]. The CEBus protocol uses a peer-to-peer communications model so that any node on the network has access to media at any time. The CEBus standard includes commands such as volume up, fast forward, rewind, pause, skip, and temperature up or down one degree. These commands are based on the application-to application communication language called the CEBus Common Application Language (CAL).

The CEBus Industry Council's (CIC) mission is to provide information to the design and development community about CEBus and CEBus Home Plug & Play. The Council involves all applicable industries and organizations in the development of interoperable products which offer the homeowner a multiple of products to choose from that can communicate with each other and work as a system. These products can ask each other questions, answer question, and provide unsolicited status reports based on what they see and know about the home's environment. These messages are passed back and forth through the home's power lines, telephone wires, television cable, infrared signals and radio signals.

CEBus allows products to share information such as time, temperature, occupancy state, status of equipment, and so on. The data allows redundant product functions to be centralized, the removal of cumbersome user interface from many products, and easy delivery of outside service information directly to products. With CEBus, equipment can simply “place” information on the network where it is picked up by other devices that can use the same information to their advantage. Information can originate in the home or from service providers outside the home.

In a network, two ingredients are basic to successful communication: transparent movement of data between nodes and/or systems; and ensuring that the data arriving for the destination node and/or system is in a meaningful form that can be immediately recognized and processed. The CEBus standard defines only those functions required to facilitate communications; it does not describe the specific implementation, design, or technologies to be used. Those are left to the innovation of the system developer. However, a full range of multi-vendor interoperability issues are definitely addressed by the standard, including items such as connectors.

5.2.1 CEBus Technology

CEBus uses spread spectrum technology to overcome communication impediments found within the home's electrical powerline. Spread spectrum signaling works by spreading a transmitted signal over a range of frequencies, rather than using a single frequency. The CEBus powerline carrier spreads its signal over a range from 100 kHz to 400 kHz during each bit in the packet [50]. To avoid data collision, CEBus uses the CSMA/CDCR protocol. Similar to HomePNA [28], this media access control protocol requires an information appliance to wait until the line is clear, which means that no other packet can be transmitted before it can send a packet.

Each CEBus has two channels: a *control channel* for real-time, short-packet, control-oriented functions, and a *data channel* for intensive data transfer. To ensure reliable, tamper-proof, private communications, the CEBus standard includes such crucial network protocol features as error detection, automatic retry, end-to-end acknowledgement, and duplicate packet rejection, as well as authenticated service to prevent tampering, and encryption to ensure privacy. The CEBus control channel communication is standardized across all media, with a consistent packet format and signaling rate, and is used exclusively to control devices and resources of the network, including data channel allocations. Data channels typically provide selectable bandwidths that can support high data rates and are used to send data such as audio, video, or computer files over the network. The characteristic of a data channel can vary greatly depending upon the medium and connected device requirements. All data channel assignments and functions are managed by CEBus control messages sent via the control channel.

5.2.2 CEBus Protocol

CEBus uses a peer-to-peer connectionless service, CSMA/CDCR communication protocol

(Carrier Sense Multiple Access with Collision Detection and Collision Resolution) [56]. The Open Systems Interconnection (OSI) Protocol Stack consists of a physical layer, a data link layer, a network layer, and a application layer Figure 5.4 illustrates how the CEBus protocol is consistent with the OSI Protocol Stack.

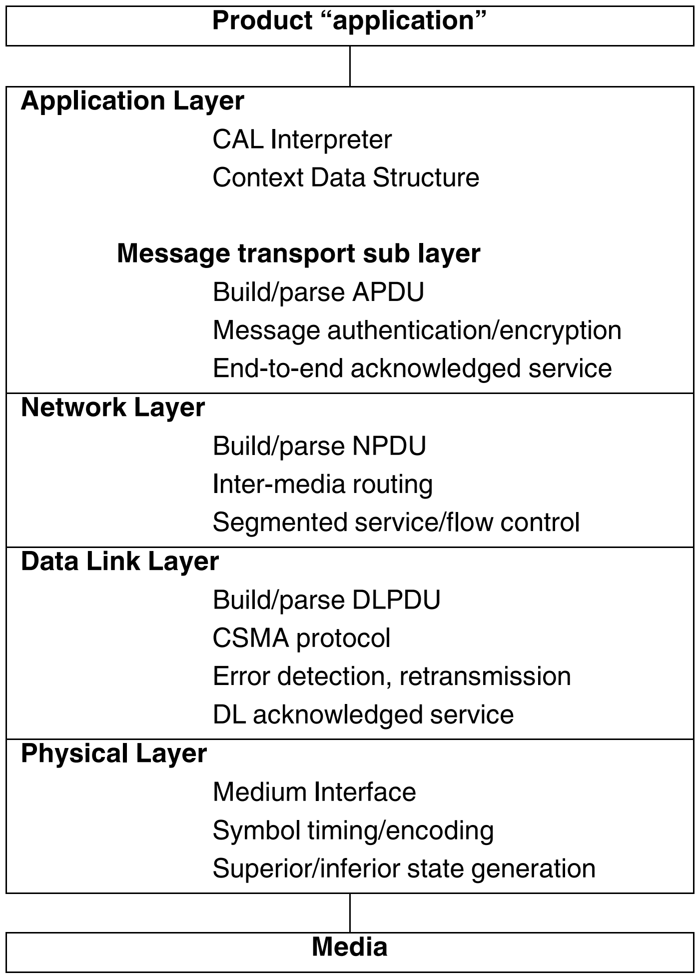

Figure 5.4 CEBus protocol "stack".

Many transport layer functions (segmented service, end-to-end acknowledgement) are incorporated into the application and network layers. Besides the protocol functions defined by the traditional OSI model, the CEBus standard defines the physical characteristics of each of the allowed media and an application language interpreter. The Common Application Language (CAL) provides a data structure model of how each function of a product operates. CAL also provides management of network resources, node status functions and address configuration.

5.2.3 CEBus Packet Structure

Figure 5.5 illustrates the breakdown of elements of a CEBus packet into logical groups with size information. A CEBus packet frame can be broken down into several parts: The Link Protocol Data Unit (LPDU), the Network Protocol Data Unit (NPDU), the Application Protocol Data Unit (APDU) and the CAL message.

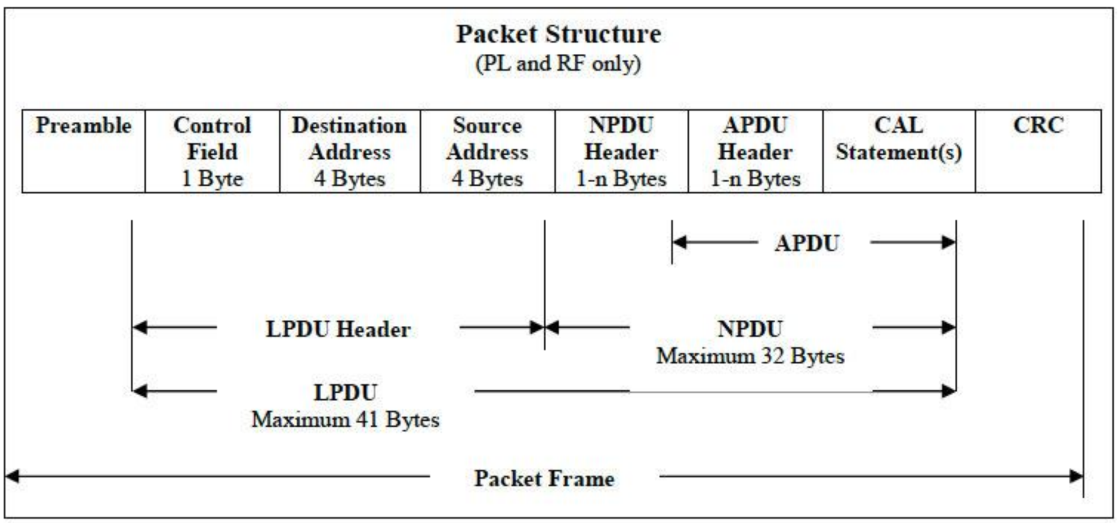

Figure 5.5 CEBus Packet Structure [Courtesy: Intellon Corporation] [56].

The CEBus packet structure reflects the contribution of each protocol layer. The APDU, generated by the message transport sublayer, contains the CAL message and the necessary application layer acknowledgement service and security service (authentication and encryption) header information. The NPDU, generated by the network layer, contains the APDU and the necessary network routing and message segmentation header information. The LPDU header contains the Control Field and the source and destination addresses. The Control Field specifies the packet type, packet priority, and service class to the Data Link Layer (DLL). The remaining parts of the packet are the preamble and the frame check sequence (FCS) or the Cyclic Redundancy Check (CRC). The CRC is a packet-level error detection field appended by the data link layer. Packets vary in size from approximately 50 bits (the smallest packet) to about 350 bits (the largest packet), depending on the size of the CAL message and the content of the layer headers.

All CEBus nodes have a unique address pair: a system address and a node address. The system address is the same for all nodes in the home, while each node address in a given system is unique. The purpose of a system address is to logically isolate the nodes in one house from the nodes in another house, particularly on medium networks that span multiple homes. Messages from a node in one system network cannot be received by nodes in another system network.

The generation of a CEBus packet is a two-step process. First the data from the host are converted to symbols. These symbols are then converted to waveforms to be transmitted. Each CEBus packet consists of a preamble, packet body, and CRC.

Intellon's spread spectrum power line technology was chosen by EIA as a result of an industry wide competitive selection. Spread spectrum has wide bandwidth which makes it immune to many frequency-dependent impairments. This is due to the fact that only a portion of Intellon's spread spectrum signal is required for detection. The signal may suffer from many different types of impairments and still provide error free communication.

5.2.4 Summary

Many CEBus complaint products for home automation are being developed including lighting and appliance controllers, wireless security systems (utilizing SSC RF Signaling), thermostats, HVAC controllers, audio/video equipment control, etc. In addition to the consumer level products that are being used, many utility providers are installing energy management systems at their customer's premises to perform meter reading, load control, and provide services such as security monitoring. There are also many commercial applications being implemented, using the CEBus PL and RF SSC signaling technology, that are not concerned about CEBus compliance. In at least one European city, public lighting is being controlled with SSC PL communications utilizing the 20 kHz to 80 kHz chirp signal [58]. CEBus communications over the electric distribution network utilizes the phase coupling mechanism for power line communications [59]. There have been two serious impediments to the growth of the powerline carrier (PLC) communications industry, the line noise, which degrades the communications reliability, and the lack of a standard communication network protocol [60]. These stumbling blocks have been removed to a greater extent, the first, by the development of spread spectrum PLC technology, which all but eliminates the noise impediment, and the second, by the industry wide adoption of the EIA's CEBus standard. Reference [61] outlines methods of communication over a powerline namely X-10 and CEBus and also introduces spread spectrum technology as to increase speed to 100-150 times faster than the X-10 system. Detailed information on the CEBus standard, development tools, training, existing products and literature can be found in [57].

5.3 Passport and Plug-in PLX

Intelogis Inc., founded in 1997 and renamed to Inari Inc. in 2000, developed one of the first powerline technologies, called Passport, which is sometimes also referred to as the original powerline technology. This section is given as a reference to discuss the Intelogis Passport powerline technology. Most of the material in this section is based on the findings reported in [62]. Passport relies on frequency-shift keying (FSK) to send data back and forth over the home electrical wiring. FSK uses two frequencies, one for 1's and the other for 0's, to send digital information between the computers on the network. The frequencies used are in a narrow band above the level of line noise occurrence. A flaw of this somewhat fragile method is that anything that impinges on either frequency can disrupt the data flow, causing the transmitting computer to have to resend the data. This can affect the performance of the network, including network slowdown. Included with the Intelogis Passport kit were line-conditioning power strips which would be inserted between the wall outlet and the user computer equipment to help reduce the amount of electrical-line noise. Based on 110-volt electrical system (which made the technology unsuitable to countries outside of North America), the Intelogis powerline network uses computer's parallel port for physical connections. It also requires the installation of software for its modules to work. Intelogis Passport technology uses client/server network architecture. This architecture is a centralized administrative system providing information to all of the other devices. The first computer on which the software is installed becomes the Application Server which controls the data flow over the network and directs each device to find other devices. Some of the disadvantages associated with the Intelogis Passport technology are highlighted below:

- Slow connection speeds (50 kbps up to 350 kbps)
- Home power usage affects performance
- Powerline Device (Module) size appears to be rather large
- Only works on standard 110-V powerlines
- All data needs to be encrypted for a secure network
- Older powerline wiring degrades performance

Taking a different track to powerline communications, Intelogis technology transmits data in a frequency band above the noise region. Dubbed as Plug-in PLX technology [63], it uses a combination of datagram-sensing multiple access (DSMA) and centralized token passing (CTP).

DSMA acts in a similar fashion to the multi-node contention resolution of an Ethernet network. A node, when entering the network for the first time, detects the carrier of the other packets on the line, sending its own packet only if it is clear to do so. Once all the nodes are known to each other, the dynamic centrally distributed token passing scheme is instituted which avoids multi-node contention and collision and thus raises the effective throughput. Intelogis claimed that its technology permits simultaneous transfer of small control packets and entertainment data (for example, MPEG-1 Audio Layer 3 music file), without interfering with each other. Plug-in PLX also conforms to the CEBus CAL [63].

5.4 X-10

X-10 (also referred to as X10) is a communications protocol that allows compatible home networking products to talk to each other via the existing home electrical wiring. The X-10 code format was first introduced in 1978 by X-10 Inc., for the Sears Home Control System and the Radio Shack Plug ‘n’ Power System [64]. The X-10 technology, now 35 years old, was initially developed to integrate with low cost lighting and appliance control devices.

X-10 compatible devices, which are electrical components directly plugged into wall outlets, can communicate with each other. But these devices are susceptible to damage by voltage spikes. Additionally, signal attenuation and line noises generated by household appliances or external sources can transiently interfere with X-10 communications. With the powerline subnet being shared among neighboring houses, X-10 commands from one house can interfere with devices in another house. As a result, reliability remains a major issue in X-10 powerline networking [65]. Complex and unanticipated faults are unavoidable in X-10 networking, and the faults manifest themselves as anomalous behavior on the powerline in terms of illegal sequences of X-10 commands. The X-10 protocol is underspecified with respect to when exactly modules get to be addressed and unaddressed (i.e., when the modules move from unaddressed state to an addressed state and vice versa). Only experimentation with various command sequences could lead to the formulation of rules governing the addressing of X-10 modules and development of a model for the legal X-10 command sequences. The X-10 powerline communication protocol and a model-based fault detection system that achieves completeness of coverage for X-10 faults are discussed in [65].

The vast majority of X-10 communication remains unidirectional only [50]. However, some capability for bidirectional communication has also been added to it. X-10 controllers send signals over existing AC wiring to receiver modules. The X-10 modules are adapters connected to outlets and controlling simple devices. X-10 transmission rate is limited to only 60 bps [50] which makes it unsuitable for carrying internet type traffic around the house. By using X-10 it is possible to control lights and virtually any other electrical device from anywhere in the house with no additional wiring. The X-10 technology and resource forum designs, develops, manufactures, and markets products that are based on this standard. X-10 Ltd., which designs its own chips for its devices, manufactures products for companies including IBM, Thomson (GE and RCA brands), Philips (Magnavox brand), Radio Shack, Leviton, Honeywell, Stanley, Ademco, and ADT among others. IBM relies on X-10 technology in its Home Director product [63]. According to X-10 group, more than 100 million units have been shipped by the company [50]. These home automation devices are called “powerline carrier” (PLC) devices and are often installed by builders who want to offer home automation as an additional selling feature. The home automation line consists of “controllers” that automatically send signals over existing electrical wiring to receiver “modules”, which in turn control lights, appliances, heating and air conditioning units, etc.

5.4.1 X-10 Transmission Theory

X-10 transmissions are synchronized to the zero crossing point of the AC power line. The design goal should be to transmit as close to the zero crossing point as possible but certainly within 200 microseconds of the zero crossing point. The X10 powerhouse power line interface models PL513 and TW523 provide a 60 Hz square wave with a maximum delay of 100 µsec from the zero crossing point of the AC power line. The maximum delay between signal envelope input and 120 kHz output bursts is 50 µsec. Therefore it should be arranged that outputs to the PL513 and TW523 be within 50 µsec of this 60 Hz zero crossing reference square wave [64].

A binary 1 is represented by a 1 millisecond burst of 120 kHz at the zero crossing point and a binary 0 by the absence of 120 kHz. The PL513 and TW523 modulate their inputs with 120 kHz, therefore only the 1 ms “envelope” need to be applied to these inputs. These 1 ms bursts should actually be transmitted three times to coincide with the zero crossing points of all three phases in a three phase distribution system. Figure 5.6 shows the timing relationship of these bursts relative to zero crossing.

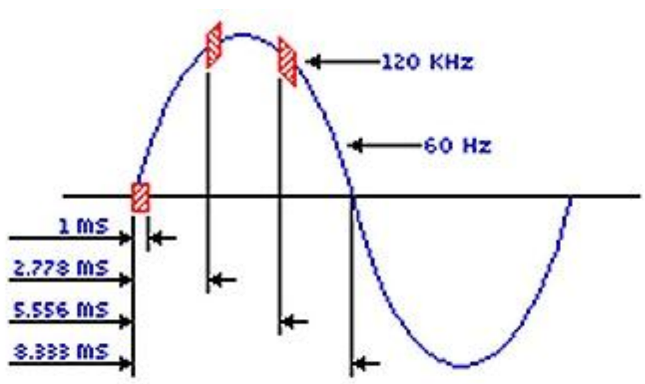

Figure 5.6 Timing relationship of X-10 signals [64].

A complete code transmission encompasses eleven cycles of the power line. The first two cycles represent a Start Code. The next four cycles represent the House Code and the last five cycles represent either the Number Code (1 thru 16) or a Function Code (On, Off, etc.). This complete block, (Start Code, House Code, Key Code) should always be transmitted in groups of 2 with 3 power line cycles between each group of 2 codes. Bright and dim are exceptions to this rule and should be transmitted continuously (at least twice) with no gaps between codes. Figure 5.7 illustrates the details of the powerline cycle usage.

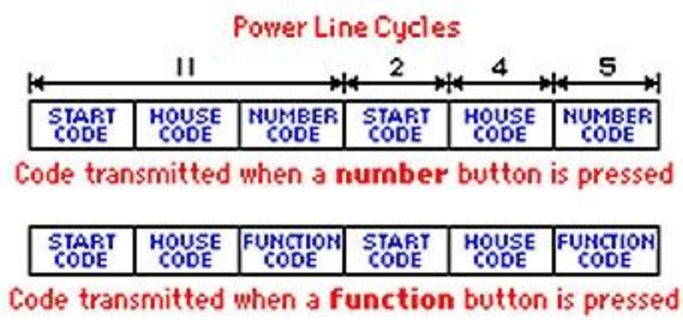

Figure 5.7 Power line cycles for X-10 code transmission [64].

The control capabilities of X-10 are depicted in the Figure 5.8.

5.4.2 Summary

The main disadvantage of the legacy X-10 technology that it has very limited capability in terms of both speed and intelligence. X-10 is a technology relegated to control application only due to its low data rate and rudimentary functionality [50]. Another disadvantage with the X-10 power line carrier (PLC) signaling “language” is that it operates on 110V AC power cycle [66]. However, the ultimate goal of X-10 technology is to provide for a higher-speed protocol that facilitates communication between home PCs and controlled home appliances.

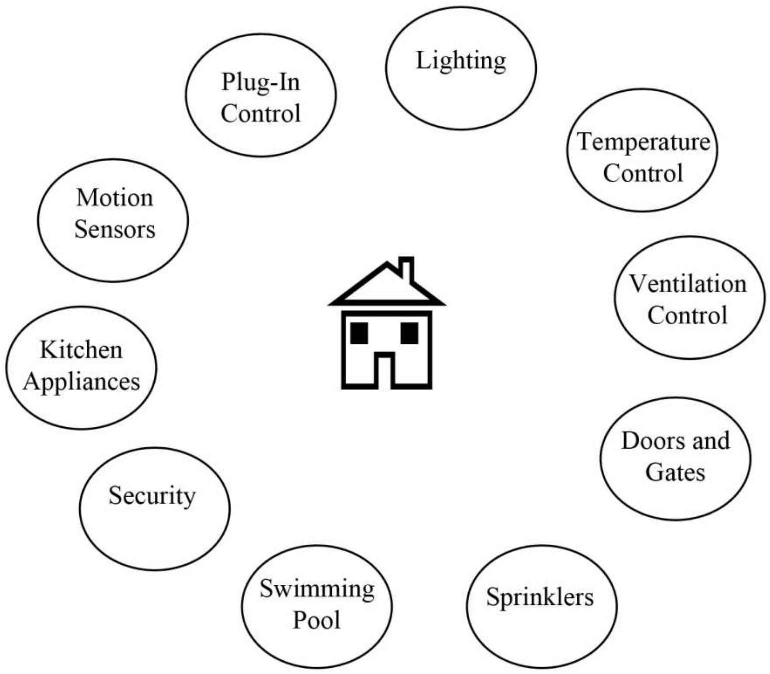

Figure 5.8 X-10 Control Capabilities.

5.5 PowerPacket

Intellon Corporation's PowerPacket™ technology which is the basis of the HomePlug Powerline Alliance industry specification, is a carefully crafted version of the Orthogonal Frequency Division Multiplexing (OFDM). PowerPacket is the brand name for Intellon's high-speed powerline communications technology that now provides a 14 Mbps data rate over existing powerlines in the home. PowerPacket is a complete solution that encompasses the physical (PHY) and media access (MAC) layers of the networking model. It supports advanced services such as voice over IP (VoIP), Quality of Service (QoS) and streaming media [67], which will provide new multimedia and telephony applications to the consumer. OFDM is a spectrum efficient modulation technique that enables transmission of very high data rates in frequency selective channels. Data rates in excess of 100 Million bits per second (Mbps) are possible [68]. PowerPacket is a multiple carrier system with characteristics that make it adaptable to environments with harsh multi-path reflections without equalization. OFDM modulation is essentially the simultaneous transmission of a large number of narrow band carriers, sometimes called subcarriers, each modulated with a low data rate, but the sum total yields a very high data rate.

5.5.1 PowerPacket Technology

PowerPacket physical layer (PHY) uses the orthogonal frequency division multiplexing (OFDM) as the basic transmission technique. PowerPacket technology also uses concatenated Viterbi and Reed Solomon FEC with interleaving for payload data, and turbo product coding (TPC) for frame control fields [68].

The high-speed data stream to be transmitted is processed as multiple parallel bit streams by OFDM, with each having low bit rate [68]. Each bit stream then modulates one of a series of closely spaced carriers. Carrier spacing is chosen to be equal to the inverse of the data rate to achieve orthogonality. OFDM carrier spacing is generally chosen such that each carrier experiences a flat response within its allocated channel bsndwidth. The need for equalization in PowerPacket is completely eliminated by using different phase modulation where the data is encoded as the difference in phase between the current and previous symbol in time on the same carrier.

OFDM waveforms are typically generated using an inverse Fast Fourier Transform (IFFT) in which the frequency domain points (input to the transform) consist of the set of complex symbols that modulate each carrier. The output of the FFT is a time domain signal, called the OFDM signal.

Since an FFT is reversible, the data can be recovered via a forward FFT, converting back to the frequency domain. Figure 5.9 illustrates the conversion process between the frequency domain and the time domain.

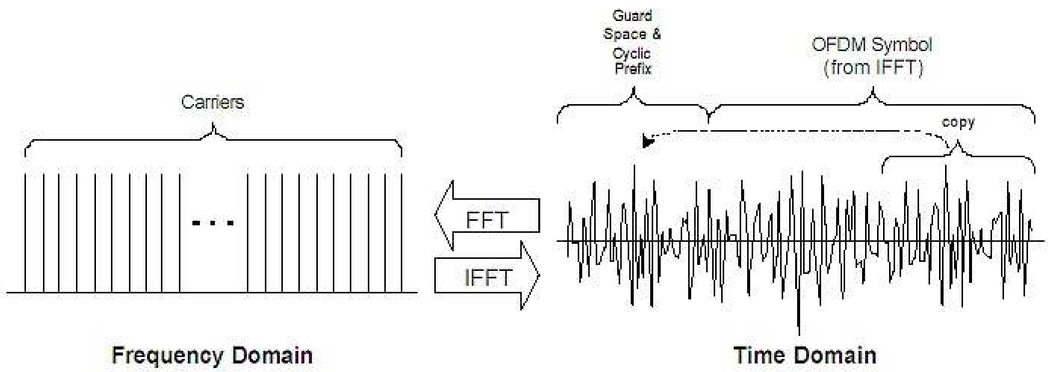

Figure 5.9 OFDM symbol creation by IFFT [Courtesy: Intellon] [68].

During signal processing, PowerPacket intelligently adds a cyclic prefix which is essentially a replication of the last few microseconds of the OFDM symbol. The cyclic prefix is basically a "throwaway" portion of the transmitted symbol allowed to be corrupted by intersymbol interference. Without the cyclic prefix, some of the samples contained in FFT would carry energy from either the previous or the following OFDM symbol.

Considering the frame format, the PowerPacket transmission frame consists of a start-of-frame delimiter, a payload, and an end-of-frame delimiter, as illustrated in Figure 5.10 below. The frame delimiters comprise a preamble sequence followed by a TPC encoded frame control field. The preamble sequence is a known pattern chosen to be reliably detected by all receivers regardless of channel conditions. Unicast transmissions are acknowledged by the transmission of a response delimiter. Start of Frame, End of Frame, and Response delimiters all have the same symbol structure but contain fields pertinent to their function. The payload portion of a frame is rate adaptive according to the channel quality between the transmitter and receiver. Rate adaption occurs in three ways: by not using same carriers to transport data; by changing the modulation of those carriers in use between DQPSK and DBPSK; and by changing the Convolutional FEC rate between ¾ and ½. The PowerPacket PHY occupies the band from 4.5 to 21 MHz. Intellon's ICs perform digital filtering to meet HomePlug's transmitter power spectral density (PSD) mask, including the 30 dB notches required to avoid interference with amateur radio operators [67]. The HomePlug PHY includes reduced transmitter power spectral density in the amateur radio bands to minimize the risk of radiated energy from the powerline interfering with these systems. The raw bit rate using DQPSK modulation with all carriers active is 20 Mbps. The bit rate delivered to the MAC by the PHY layer is about 14 Mbps [69].

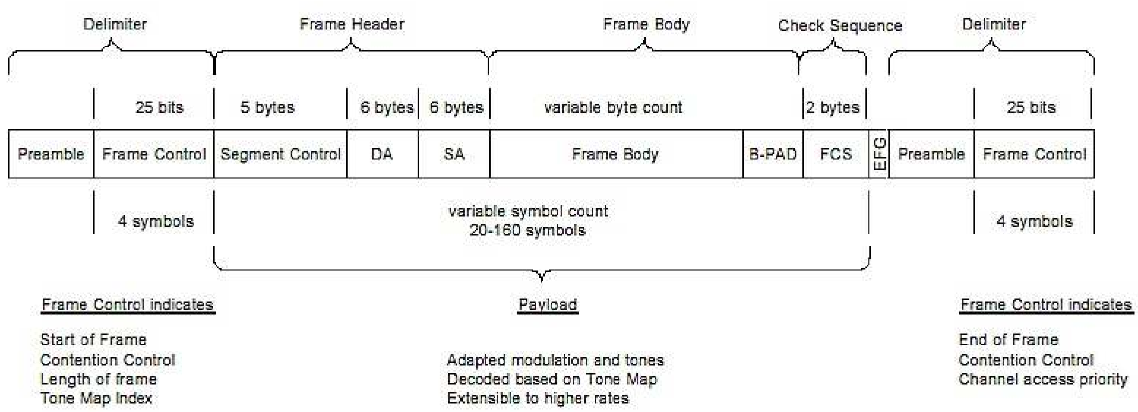

Figure 5.10 PowerPacket Frame Format [Courtesy: Intellon] [68].

The MAC protocol in the PowerPacket technology is a variant of the well-known carrier sense multiple access with collision avoidance (CSMA/CA) protocol, similar to the IEEE 802.11 specification. The PowerPacket MAC protocol uses a classic, listen-before-talk strategy and transmission after a randomly selected delay to avoid collisions [67]. This virtual carrier sense (VCS) mechanism and contention resolution helps minimize the number of collisions [69]. Addition of several features enables the protocol to support priority classes, provide fairness, and allows the control of latency.

Since PowerPacket is rate adaptive, the transmission time for a given packet size varies. Long transmission times thwart a protocols ability to offer Quality of Service (QoS) since a high priority frame may be forced to wait for a long, slow transmission to complete. To overcome this problem PowerPacket requires the segmentation of frames that exceed certain duration. Higher priority frames can then jump in between the slower transmission's segments. To reduce the chance for collision among equal priority members, PowerPacket uses segment bursting, which allows all segments of packet to be transmitted back-to-back unless interrupted by a higher priority. An extension of this capability is contention-free access in which a station transmits a limited number of frames to different destinations without interruption. Contention-free access improves QoS for certain types of multimedia traffic [67] such as voice-over-IP (VoIP) or streaming media [69].

PowerPacket's privacy mechanism creates a logical network with all nodes in the network sharing a common encryption key. Encryption of all frames is performed at the MAC layer by a 56-bit data encryption standard (DES) algorithm using cipher block chaining. The key management systems include features that enable the distribution of keys to nodes that lack an I/O capability.

5.5.2 Summary

Intellon's PowerPacket technology serves as the basis for the HomePlug Powerline Alliance standard. Using the enhanced OFDM, the rate-adaptive design allows PowerPacket to maintain an

Ethernet-class connection throughout the power-line network without losing any data. Some of the advantages of PowerPacket include the following [62]:

- Fast, data rate of 14 Mbps
- Avoids disruptions in the powerline, maintaining the network's connections and speeds
- Printer features are not limited
- Compatibility with different Operating Systems
- Embedded circuitry in the device enables only the standard power cord to access an AC outlet
- Works independently from the line voltage and frequency
- 56-bit DES encryption is included
- Tests show negligible signal degradation due to older wiring

PowerPacket devices connect via a USB or Ethernet cord to the computer or other devices and on the other end to the AC outlet. PowerPacket uses a peer-to-peer network architecture (which eliminates the need for consulting a central system first).

The latest generation of PowerPacket is rated at 14 Mbps, which is faster than existing phone-line and wireless solutions. However, as broadband access and Internet-based content including streaming audio and video and voice-over-IP (VoIP) become more common, speed requirements will continue to rise. Along these lines, the Intellon's OFDM approach to power-line networking is highly scalable, eventually allowing the technology to surpass 100 Mbps [62]. The exact methods of scaling the PowerPacket technology to higher speeds are proprietary by Intellon [68], however, the suggested areas of focus are modulation techniques, protocol enhancements, and circuit design optimization.

5.6 Cogency's HomePlug Technology

Established in 1997 and based in Toronto, Canada, Cogency Semiconductor Inc. [70] addresses the technical challenges encountered using powerline for data communications by providing integrated circuits, offering a robust, cost-effective, high-speed technology solution for networking, entertainment and computer products. Cogency's HomePlug technology combines OFDM, signal coding, and error correction techniques.

Cogency's technology for powerline networking includes a physical layer (PHY) and Medium Access Control (MAC) layer. The PHY layer implements the modulation techniques, the coding, and basic packet formats. The PHY uses packet-based OFDM as the transmission technique. The MAC uses a CSMA/CA protocol to mediate access between multiple clients [71].

The Cogency MAC/PHY provides per packet equalization and efficient access to the shared powerline medium. Additionally a proprietary resolution signaling scheme enables latency-sensitive applications such as voice-over-IP (VoIP) and multi-player gaming.

The Cogency MAC/PHY uses OFDM technology for signal transmission at a high data rate with few bit errors. OFDM modulation generates a set of tones in the frequency domain. Resistance to deep, narrow fades is provided by using many carriers. The loss of few tones can be compensated for with the Forward Error Correction (FEC) coding which redundantly encodes data across all active tones. Automatic channel adaptation allows the system to respond to current conditions on the powerline. The tones are modulated using either differential BPSK (76 bits per OFDM symbol) or QPSK (152 bits per OFDM symbol). For harsh channels or when channel adaptation has not been performed, the payload data is sent using ROBust OFDM (ROBO) mode. ROBO mode uses all available tones with differential BPSK modulation on each tone, as well as heavy error correction and interleaving. ROBO mode is useful for very harsh channels or when establishing initial contact with another device to negotiate the optimum communication scheme. Convolutional or Reed-Solomon coding are used for payload data. Convolutional coding rates of ½ can be punctured to achieve a rate of ¾. A combination of coding rate and modulation is used to adjust to varying channel conditions. Product encoding is used for frame control fields, which ensures that all devices on the network are able to detect and decode this information. Channel adaptation is used to specify modulation or coding schemes for payload data. If significant fading occurs, specific tones can be dropped from the transmission. Data packets can be transmitted in two modes: to all stations, or to one specific station. Data is encoded on all carriers when transmitting frame control symbols. Reliability of transmission is ensured by the MAC/PHY layer's acknowledgment of Unicast transmission by sending a response delimiter (ACK) to indicate a successful transmission. A NACK signal is sent to indicate that the packet was received but with errors. The MAC/PHY uses Automatic Repeat request (ARQ) to guarantee reliability. Receipt of a NACK (or no response) results in the packet being resent. The MAC/PHY layer can determine the state of powerline by monitoring the frame delimiters. This is known as "carrier sense". For reduction of collisions that occur with random access to the channel, Cogency uses a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol enhanced with priority signaling. Prioritized access to the channel is achieved by using the Priority Resolution Period. Cogency's HomePlug technology provides a robust solution to the powerline networking, providing reliable data transmission for the home networking environment. The Cogency MAC/PHY layer adapts automatically to changing conditions on the powerline providing a reliable channel under the noisiest conditions. Multipath distortion effects are taken care of with the OFDM technology. Privacy management using 56-bit encryption techniques provides privacy, while priority contention control ensures timely access for latency-sensitive applications. Cogency's HomePlug technology provides Ethernet-class data networking and supports VoIP, QoS, and streaming media applications.

5.7 Conclusions

PLC systems represent a relatively recent and rapidly evolving technology, aimed at the utilization of the electricity powerlines for the transmission of data. This chapter presented an in-depth technical analysis of all the existing technologies associated with the powerline carrier communications systems. Powerlines are inherently the most attractive medium for home networking due to its universal existence in homes, the abundance of AC outlets and the simplicity of the power plug. In comparison, the phone line suffers from too few connection points and wireless connections from congestion at 2.4 GHz, as well as interference [72]. The potential for powerline to act as a backbone for home networking is great, provided that the powerline is able to provide reliability, security and robustness to meet the requirements of the most demanding applications.

As many companies have developed their own (and sometimes proprietary) systems for dealing with the powerline networking, there was a need for standardization, which was covered in Section 1.4 of this thesis. The four driving needs for a home network are home automation, home computer, audio and video distribution, and an access network. CEBus aimed at control, makes HomePlug the ideal choice for home networking scenario. CEBus, X-10, and LonWorks core technologies are more suited to home control and automation systems. HomePlug certified products deliver data at 14 Mbps and the flexibility of Intellon's enhanced OFDM (which is the basis of HomePlug specification) allows scalability to very high data rates, upto 100 Mbps and beyond.

6. Powerline Communication Systems Analysis

6.1 The powerline channel model

In order to perform computer simulations oriented to the design of communications systems, models of the channel transfer characteristics are of major interest. For the design and computer-based performance analysis of modulation schemes, the complex frequency response or the impulse response of powerline links are required. The development of a powerline communication system requires measurement-based models of the transfer characteristics of the mains network suitable for performance analysis by simulation.

A powerline channel model is described using the top down strategy (mentioned in Chapter 4) considering the communication channel as a black box and described by its frequency transfer characteristics $\underline{H}(f)$ in the range from 500 kHz up to 20 MHz using only a very few relevant parameters. The structure of this model is based on fundamental physical effects, which were analyzed with numerous measurements [73]. The relevant parameters are derived from frequency response measurements. The parameter estimation strategy is described in [73].

Only in the case of very simple topologies, such as a power cable with a single branch, the physical reasons for the observed results (cable loss, reflection, and transmission factors) can be easily identified. In real network topologies, which are always more complicated, a back-tracing of measurement results to physical reasons will generally turn out to be impossible. The model described here will nevertheless describe the frequency response with sufficient precision. The parameters, however, cannot be directly derived from physical properties of the network.

Equation (4.6) describes a simplified parametric model describing the complex frequency response of typical powerline channels covering all substantial effects of the transfer characteristics in the frequency range from 500 KHz to 20 MHz by a small set of parameters which can be derived from measured frequency responses as mentioned in [73]. Moreover, the number of paths, N, allows a control of the precision of the model, which is especially important for defining reference channels for PLC system performance analysis. The complex frequency response of the simplified parametric model combining multi-path propagation, signal attenuation and delay described in Eqn. (4.6) is as follows with Table 6.1 presenting definitions of the parameters:

$$\underline{H}(f) = \sum_{i=1}^{N} g_i \cdot e^{-(a_0 + a_1 f^k)\cdot d_i} \cdot e^{-j2\pi f \frac{d_i}{v_p}} \qquad (4.6)$$

i	Number of path, where the path with the shortest delay has the index i=1
a_0, a_1	Attenuation parameters
k	Exponent of the attenuation factor (typical values are between 0.5 and 1)
g_i	Weighing factor of the path *I*, in general complex, can be considered as combination of the involved reflection and transmission factors
d_i	Length of the path *i*
v_p	Velocity of propagation of the cable

Table 6.1 Model parameters for the powerline channel transfer function.

This parametric model is applied to the network topology shown in Figure 6.1 to explain the multipath signal propagation behavior exhibited by a typical powerline channel.

Multipath signal propagation is studied by a simple example which can be easily analyzed as illustrated in Fig. 6.1. The link has only one branch and consists of the segments (1), (2) and (3) with the lengths l_1, l_2, and l_3 and the characteristic impedances Z_{l1}, Z_{l2}, and Z_{l3}. It has four nodes A, B, C and D with characteristic impedances Z_A, Z_B, Z_C, and Z_D respectively at each node.

In order to simplify the considerations, A and C are assumed to be matched, which means $Z_A = Z_{l1}$ and $Z_C = Z_{l2}$. The remaining points for reflections are B and D, with the reflection factors denoted as

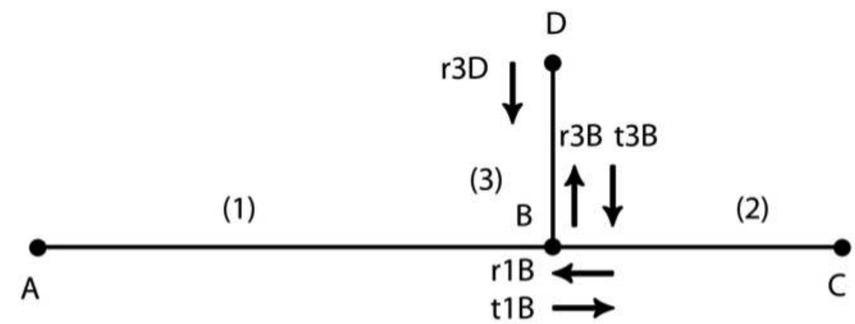

Figure 6.1 Multipath signal propagation: cable with one tap.

r1B, r3D, r3B, and the transmission factors denoted as t1B, t3B. With these assumptions, an infinite number of propagation paths is possible in principle, due to multipath reflection (i.e., A→B→C, A→B→D→B→C, A→B→D→B→D→B→C, and so on). Each path *i* has a weighting factor g_i representing the product of the reflection and transmission factors along the path. All reflection and transmission factors at the powerlines are basically less than or equal to one. This is due to the fact that transmission occurs only at joints, where the load of the parallel connection of two or more cables leads to resulting impedance being lower than the characteristic impedance of the feeding cable. Hence, the weighting factor g_i is also less or equal to one.

The parametric determination method presented in [73] are applied to the network having a topology according to Figure 6.1 with the following characteristics:

The transmitter and the receiver are located at position A and C, respectively. Terminals A and C are matched to the characteristic impedance of the cable and the point D is left open, exhibiting a reflection factor r=1. The length of the sections (1), (2) and (3) are respectively 50m, 20m and 10m.

The characteristic impedance of these cables (straight energy distribution cable of type NYM $3x1.5mm^2$) is approximately 80Ω.

From the above considerations, a channel based on this four path model is described with N=4 and parameters from Table 6.2.

Attenuation parameters					
k=0.75		a_0=0		a_1=1.22*10^{-7} s/m	
Path-parameters					
i	g_i	d_i /m	*i*	g_i	d_i /m
1	0.64	70	3	-0.15	110
2	0.38	90	4	0.05	130

Table 6.2 Parameters of a four-path channel model describing the test network.

For verification of the chosen model, the results of simulations based on Eqn. (4.6) are compared with the measurements described in [73]. From the test network described in [73] which uses the same parameter values from Table 4.2, Fig. 6.2 describes the measurements and simulation results. The results from Figure 6.2 shows that the results obtained for the particular four path channel model chosen above are in fair agreement with the one described in [73]. Also, the simulation and measurement results differ only in minor details.

To test the capability of the channel model described above for real-world networks, as an example of a frequency response with significant frequency selective fading, Figure 6.3 shows the measurement and simulation (based on Eqn. (4.6)) results of a 110m link recorded in an estate of terraced houses with 6 branches, each exhibiting a length of about 15m. The very deep notches are a consequence of multipath propagation caused by equally spaced branches of approximately the same length. To demonstrate the capability of the channel model for covering the complex frequency response of the links with multiple propagation paths, the result of a simulation based on

Eqn. (4.6) is also plotted in Fig. 6.3 for comparison. Especially in the frequency range below the first notch (4.5 MHz), the model results in an excellent match to the measurement. Up to 15 MHz, there are only minor differences between simulation and measurement, and even above 5 MHz there is still fair coverage.

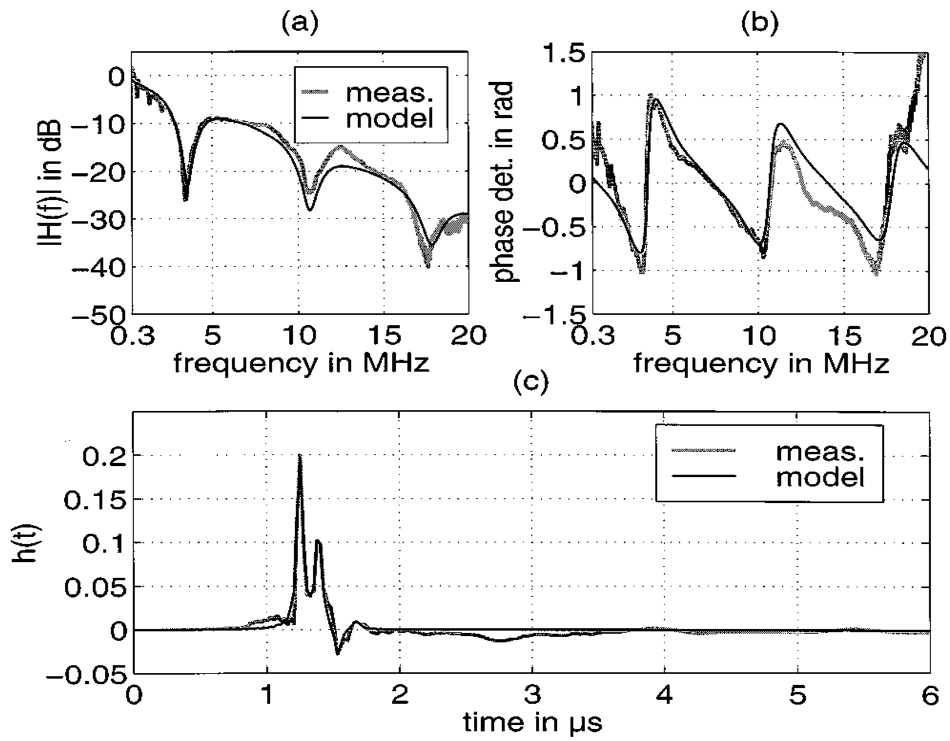

Figure 6.2 Test network: measurement and simulation with N=4 paths; a) amplitude response b) phase details, and c) impulse response [73].

The remaining deviations are due to the limited number of paths and the parameter estimation accuracy. Also, for the impulse response (in linear scale), the amount of agreement, or match, is fairly good over the complete time interval.

The amplitude response determines the signal voltage attenuation, when the signal propagates through the channel from the transmitter and receiver. Furthermore, the signal attenuation together with a signal-to-noise ratio and with the available bandwidth determines the maximum data rate. In addition to the amplitude response, the phase response is also an important parameter when considering the quality of the channel for digital communication. For the channel the linear phase response is a desirable characteristic. To get a better insight into frequency ranges with phase distortions, a more detailed phase plot is generated by subtracting the linear phase portion since the propagation time of the signal leads to large overall phase values. Due to the phase non-linearity, the waveform of the transmitted symbol changes when propagating through the channel from the sending point to the receiving point. Furthermore, the impulse response confirms the multipath aspect of the channel and shows the different significant paths. The dominant paths of the impulse response are sufficiently captured by the simple four-path channel model.

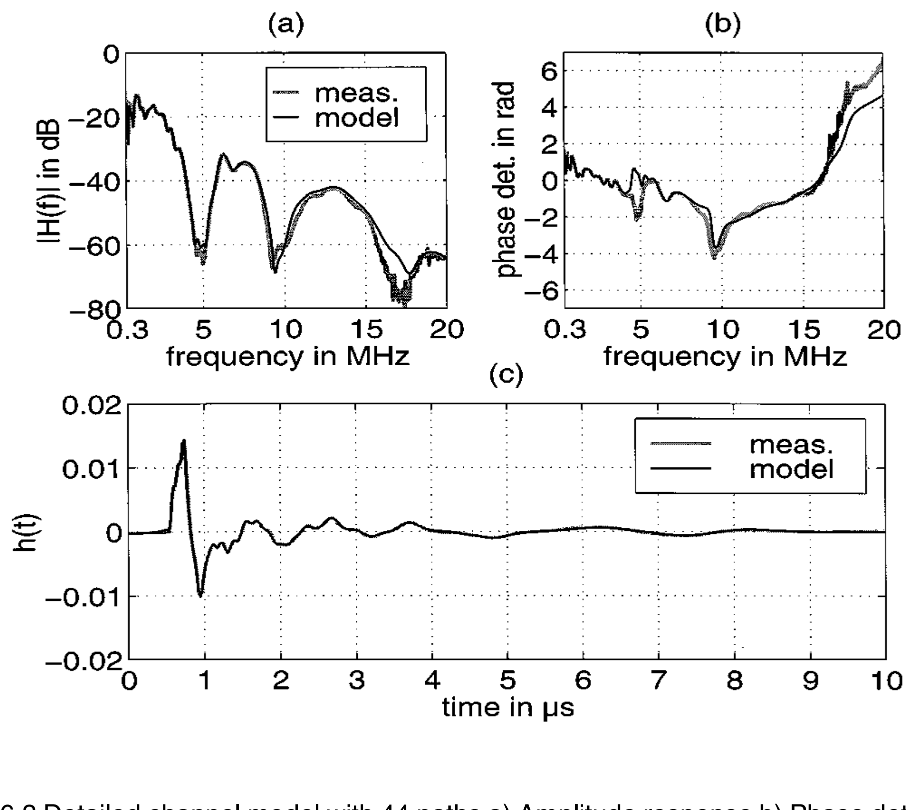

Figure 6.3 Detailed channel model with 44 paths a) Amplitude response b) Phase details c) Impulse response [73].

The example clearly points out that the essential effects of signal propagation over powerlines can be adequately described by a channel model based on Eqn. (4.6). However, for precise results, sometimes numerous paths (44 in the presented case) with individual weighing factors g_i and lengths d_i may be needed. Fortunately, on the other hand, a single set of attenuation parameters, namely k=1, a_0=0 and a_1=2.5x10^{-9} s/m, is normally sufficient. Nevertheless, it must be admitted that a channel model including a total number of 44 paths and 91 parameters is not easy to handle, and also the estimation of the parameters is quite difficult.

For PLC system performance analysis, it is desirable to have simplified channel models with only a small number of paths to represent, not all the details, but the essential dominant effects. A simplified model of the 110m link described earlier is plotted in Fig. 6.4. The channel model has been reduced to N=15, covering the main paths for the impulse response. Due to the reduced number of paths, the frequency response of the model and measurement exhibit some differences above 4MHz, especially at the locations of deep notches. However, the impulse response is still quite accurately represented by the model. The parameters of the 15-path model are listed in Table 6.3. This example clearly demonstrates the accuracy of the channel model applied to a real-world scenario strongly depends on the number of paths N and on the exact parameter settings. However, with regard to practical applications, such as simulation-based PLC-system performance evaluation, it is more important that the channel model represents the essential effects only, i.e., using well-defined reference channels. As such reference channels cover the general impairments of powerline links and do not focus on unimportant details, they may represent useful and effective tools in practice.

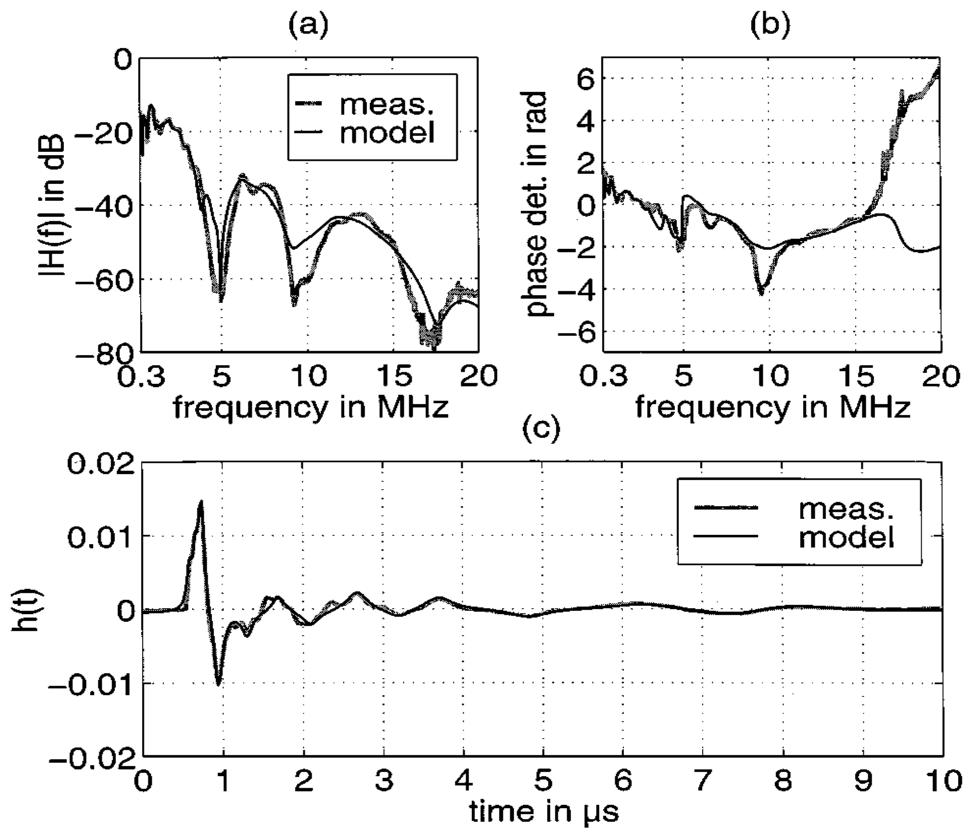

Figure 6.4 Reference channel model with 15 paths: a) Amplitude response, b) Phase details, and c) Impulse response.

attenuation parameters					
k=1		a_0=0		a_1=7.8x10^{-10} m/s	
Path-parameters					
i	g_i	d_i/m	*i*	g_i	d_i/m
1	0.029	90	9	0.071	411
2	0.043	102	10	-0.035	490
3	0.103	113	11	0.065	567
4	-0.058	143	12	-0.055	740
5	-0.045	148	13	0.042	960ad
6	-0.040	200	14	-0.059	1130
7	0.038	260	15	0.049	1250
8	-0.038	322			

Table 6.3 Parameters of a 15-path channel model.

We now create a channel model based on Eqn. (4.6), taking the four path model described in this section and produce a representative snapshot of the PLC channel. Figures 6.5 - 6.7 presents the simulation results, describing the magnitude response, phase details and impulse response, respectively, of the four path model. The results were obtained using Matlab software. The reflections at the open tap cause periodical notches in the amplitude response, which can be easily seen in Figure 6.5. The phase distortions can be seen in Figure 6.6. The impulse response, illustrated in Figure 6.7, clearly exhibits the effects of multiple propagation paths along the powerline cable.

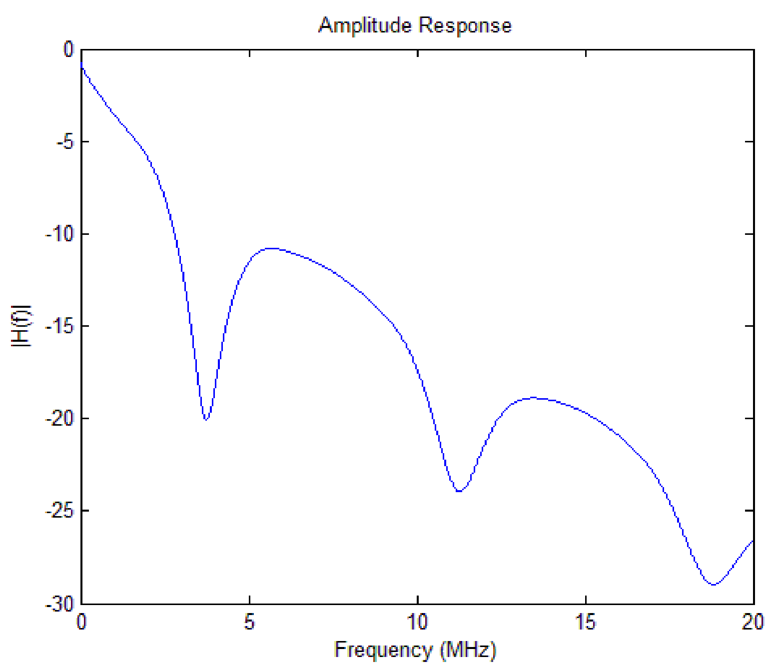

Figure 6.5 Amplitude response of the test model.

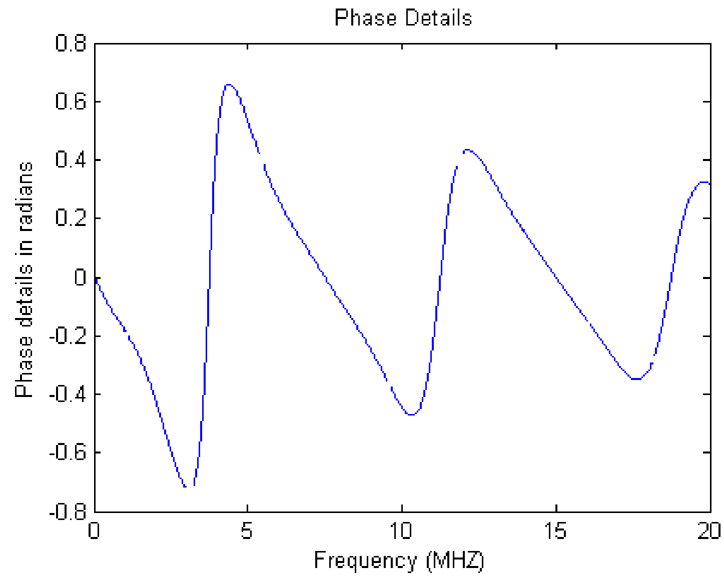

Figure 6.6 Phase details of the test model.

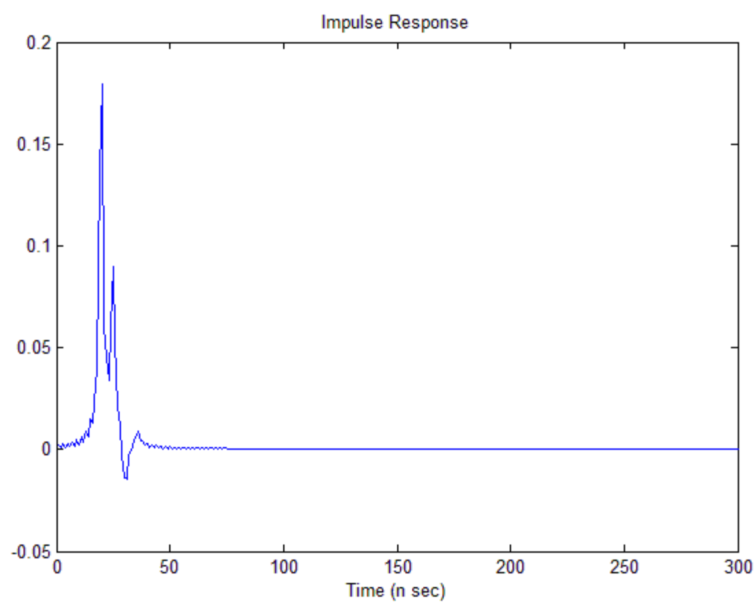

Figure 6.7 Impulse response of the test model.

These figures, which are a reproduction of the test model, certainly provide a match very close to the particular realization shown in Fig. 6.2.

In this section, a model of the complex frequency response of PLC links for the frequency range from 500KHz to 20 MHz has been derived from physical effects, namely multipath signal propagation and typical cable losses. Measurements taken from a test network with well-known parameters prove good agreement between simulation and measurement results. Furthermore, the applicability of the model to real-world networks has been demonstrated. The model developed in this study offers the possibility to carry out investigations for different network topologies and to study their impact on PLC-system performance by means of simulations. Furthermore, reference models of typical channels can be defined for standardized PLC- system evaluation and performance comparison.

6.2 Overall system Configuration

In order to study and analyze the performance of the powerline channel multi path model, we define a PLC system for communicating digital data. Figure 6.7 illustrates a general Single Carrier Modulation (SCM) system block diagram used for this purpose. BPSK modulation is used as the modulation scheme.

Each communication channel exhibits its own unique profile, due to individual network structure, dominant effects of signal propagation and an individual noise spectrum. Nevertheless the channels can be assigned to groups depending on length, type of cable and number of branches. To each group a typical reference channel is allocated. These reference channels are employed for direct examination of characteristic channel properties and for system evaluation.

When simulating the overall system performance, two reference channels are considered, namely RC1 and RC2, as a good channel and a mildly bad channel, respectively. These two extreme

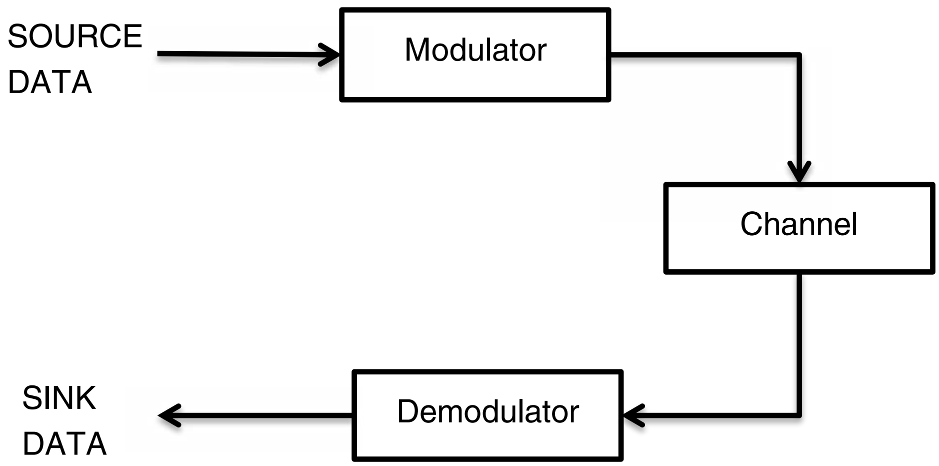

Figure 6.8 SCM System block diagram.

channels are considered in order to assess the overall system performance variation under different channel behaviors. Figures 6.9 and 6.10 show the frequency response and phase response of RC1 and RC2 used in our system simulation model. These channels show similar behavior to the reference channels mentioned in Chapter 4.

Channel RC1 is a representative of a good powerline channel. It is based on a link at a length of approximately 100m without branches. This type of links inherits only few reflection points. In residential areas with equidistant row houses and house connecting cables of similar lengths, the frequency response may exhibit deep notches. Channel RC2 is a link of that type at a length of approximately 110m with 6 branches. With increasing length this regular network structure may result in very steep frequency responses with deep fading.

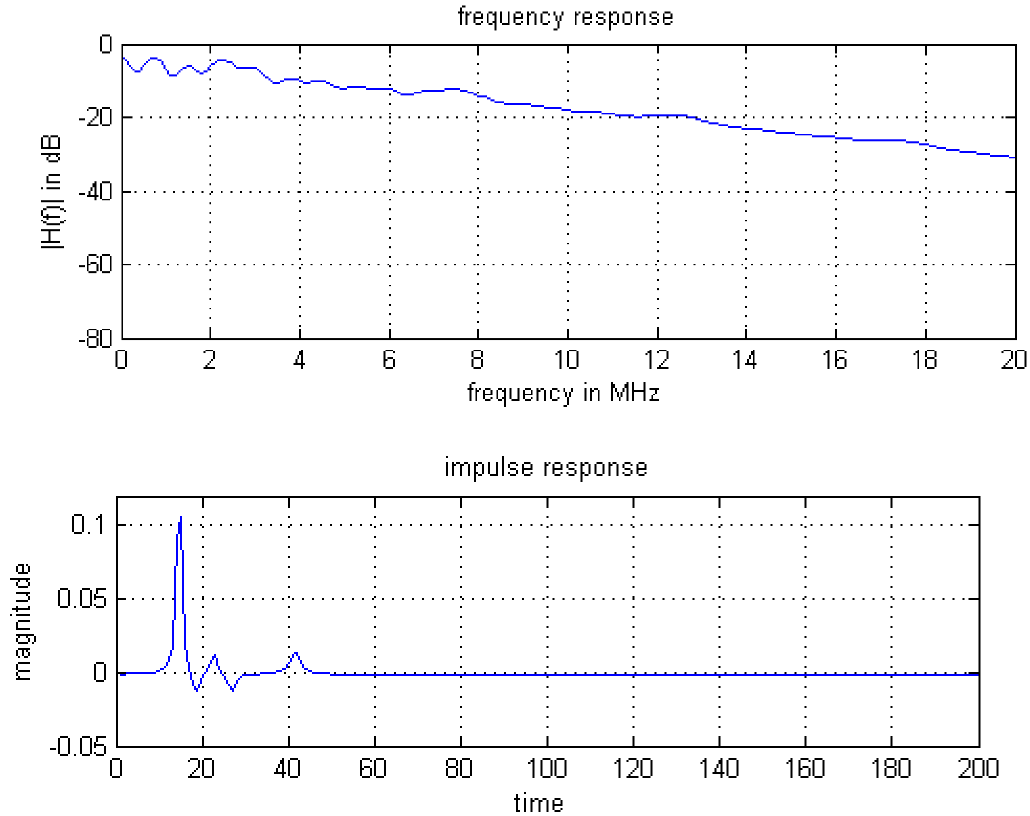

Figure 6.9 Frequency and impulse responses of Reference Channel 1 (RC1).

attenuation term:		
k=1	a_0=0	a_1=1.5x10^{-9}
path parameter:		
i	g_i	d_i
1	0.6	100
2	-0.08	130
3	0.08	160
4	-0.08	190
5	0.15	300

Table 6.4 Parameter sets for Reference Channel RC1.

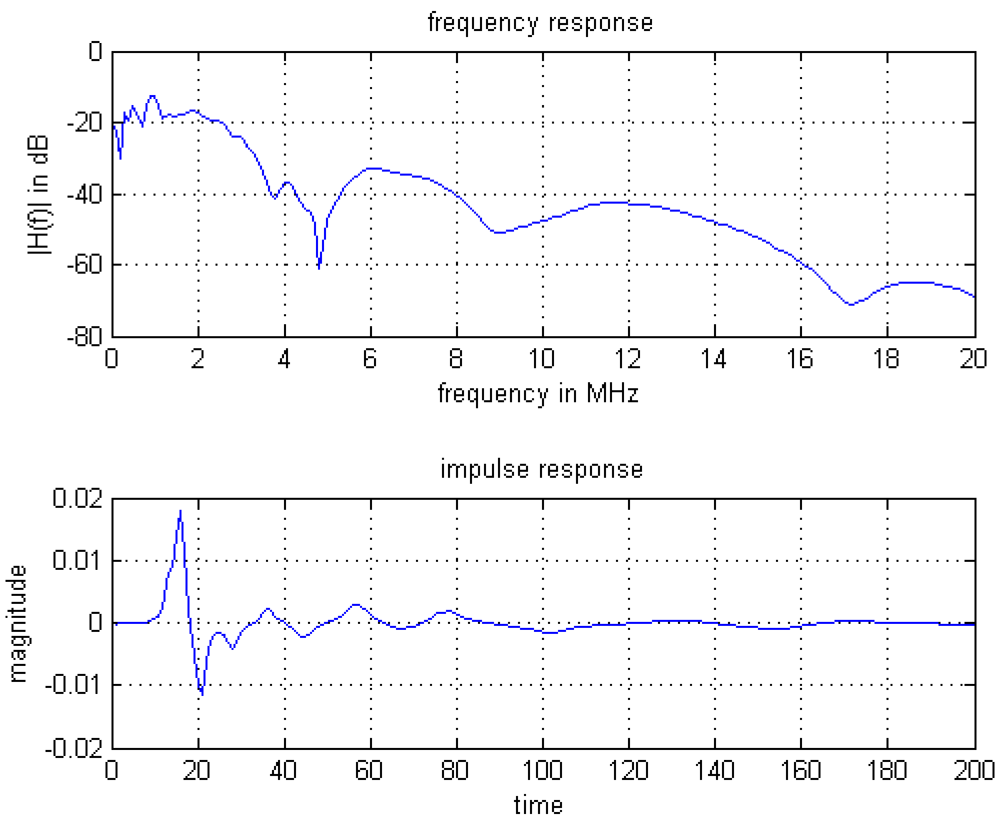

Figure 6.10 Frequency and impulse responses of Reference Channel 2 (RC2).

The Parameter sets of reference channels RC1 and RC2 are designed using Eqn. (4.4) and whose parameter values are taken from Tables 6.4 and 6.5.

attenuation term:				$k=1$	$a_0=0$	$a_1=2.5 x 10^{-9}$		
path parameter:								
i	g_i	d_i	i	g_i	d_i	i	g_i	d_i
1	0.103	113.2	6	-0.040	200	11	0.065	567
2	0.029	90.1	7	0.038	260	12	-0.055	740
3	0.043	101.8	8	-0.038	322	13	0.042	960
4	-0.058	143	9	0.071	411	14	-0.059	1130
5	-0.045	148	10	-0.035	490	15	0.049	1250

Table 6.5 Parameter sets for Reference Channel RC2.

6.3 Performance evaluation

In this section, the bit error rate (BER) analysis of binary phase shift keying (BPSK) modulation used in conjunction with a multipath PLC channel, and corrupted by additive white Gaussian noise (AWGN), is presented by means of computer simulations.

In order to perform a system level simulation of BPSK transmission over a powerline channel, a Matlab Simulink model was constructed as shown in Fig 6.11. By adding the powerline channel impulse response into the system, it is possible to analyze the system BER performance obtained in a realistic powerline communication environment.

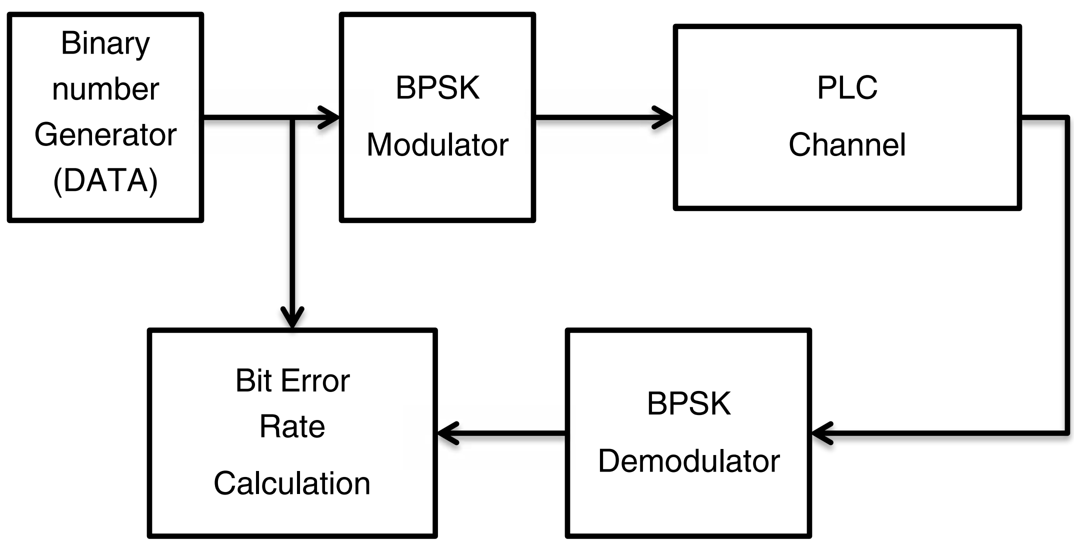

Figure 6.11 Block diagram of the PLC system used for Matlab/Simulink simulation.

In order to obtain correct simulation performance results, the simulation model used in Matlab/Simulink environment is calibrated with an AWGN channel so that the communication system with the signaling scheme used matches the theoretical BPSK curve. This is done by first determining the input signal power to the receiver. The noise variance is then adjusted for each SNR value. The results are thus calibrated with respect to the AWGN channel.

Now PLC system performance is to be considered using a multipath channel (for both RC1 and RC2) across the same SNR values to obtain the BER performance results. The noise variance is then recomputed so that it is properly scaled knowing that the signal power is changed for the multipath channel under consideration. Then, the worse channel is taken into account and the channel output signal power is obtained for RC2. The signal power is measured and used to calibrate the necessary noise variances for each SNR value considered. Thus, the noise variance is changed to get the correct value of SNR and also calibrating the system in the process.

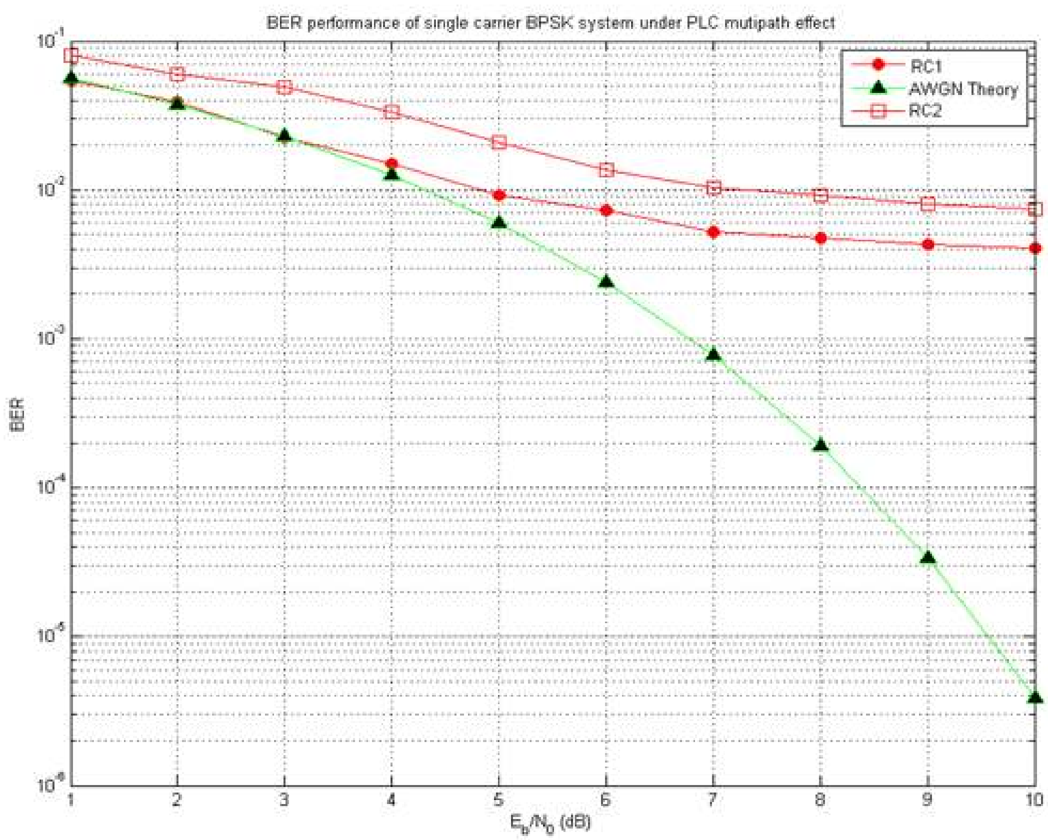

Figure 6.12 BER performance of single carrier BPSK system under PLC multipath effects.

Figure 6.12 shows the BER performance of the single carrier BPSK system used in the simulation model described here where the reference channels RC1 and RC2 are employed. Figure 6.13 shows the BER performance of a multicarrier OFDM system [75] under similar conditions that were considered in the single carrier modulation system simulation performed in this study. Comparing Figures 6.12 and 6.13, we observe a similarity in the error probability performance under low SNR conditions.

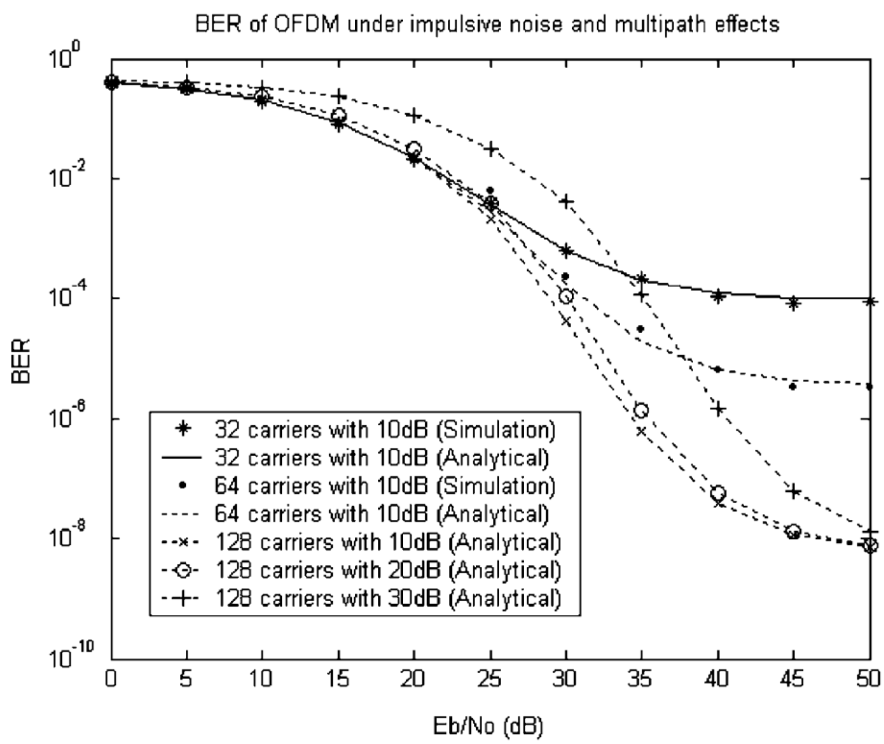

Figure 6.13 BER performance of OFDM system under multipath effects [75].

In this section, the bit error rate analysis of BPSK modulation in the presence of AWGN channel is presented by means of simulations through a PLC channel under multipath effects and is compared with a multicarrier scheme under low SNR conditions. Compared to the single carrier

BPSK scheme used in this work for PLC system performance evaluation, we observe that even the best system currently used in practice, namely OFDM, exhibits BER performance that plateaus when transmitting over a PLC channel. This BER error floor of the BER performance is caused by the PLC channel multipath effect.

6.4 Conclusion

In this chapter, by using an example of BPSK modulation, we have demonstrated that the performance is markedly compromised by the multipath effect present on the PLC channel. Even for large SNR, the performance quality is limited. In addition, there is a great variability in channel structures due to the network topology formed by the power grid. So the error probability performance is extremely variable across a power grid.

7. Summary and Conclusions

There has been a growing interest in the possibility of exploiting the power grid to provide broadband internet access to residential customers. The attractive feature of this idea is the presence of a vast infrastructure in the place for power distribution, and the penetration of the service could be much higher than any other wired alternative. Access to the internet is becoming as indispensible as access to electrical power. Since devices that access the internet are normally plugged into an electric outlet, the unification of these two networks seems a compelling option. Other broadband alternatives such as digital subscriber line and cable modems have only 10 percent of U.S. households, even though 60 percent of households are connected to the internet. There is a tremendous opportunity for powerline communications to bridge this gap. There is also growing interest in the prospects of reusing in-building powerline cables to provide a broadband LAN within the home or office. The major advantage offered by powerline based home networks is the availability of an existing infrastructure of wires and wall outlets, so new cable installation can be avoided.

Despite the enormous potential, there is some skepticism about the technology and its commercial viability. This is due to several technical problems and regulatory issues that still remained to be solved:

- The powerline channel is a very harsh and noisy transmission medium, and also it is difficult to model accurately.

- The powerline channel poses unique challenges to the communication system designer with respect to issues such as choice of appropriate modulation, coding, and detection schemes.
- Regulatory issues naturally arise due to the unshielded nature of powerline cables, which are both the source, and target, of electromagnetic interference.
- Other issues include the presence of transformers, feeder segmentation, and electrical safety.

Although the many technical and regulatory issues cause some skepticism, there is today renewed interest in powerline communications. In Europe and United states, power utility companies are partnering with vendors to conduct field trials. Moreover, in the United States an industry consortium, HomePlug, has agreed on a specification for indoor powerline-based home networking. These specifications are also selected as a baseline technology for the IEEE's 1901 Broadband Powerline Standard since it is the most widely deployed technology.

The powerline possesses unique challenges in modem design, channel modeling, medium access, and many other aspects of communications architecture. Many of these challenges have only been partially addressed and solved to date. In fact, this thesis has attempted to focus on providing a general powerline communications systems overview, as well as a detailed channel model analysis along with assessing its affect on system performance. But a solid communications and information theoretic approach is still lacking. This thesis will hopefully inspire additional theoretical work that will lay the foundation for a new generation of communications technology that can enable effective and reliable data transmission over the electric power grid.

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