PLCC Channel Modelling and Effect of Physical Parameters on its Bandwidth

Thesis submitted in partial fulfillment of the requirement for the award of degree of

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DECLARATION

*I hereby declare that the report entitled "**PLCC Channel Modelling and Effect of Physical Parameters on its Bandwidth**" is an authentic record of my own work carried out as requirements for the award of degree of M.E. (Electronic Instrumentation & Control) at Thapar University, Patiala, under the guidance of Dr. Mandeep Singh (AP, EIED) during January to July 2010.*

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ABSTRACT

Power Line Carrier Communication (PLCC) is relatively new candidate in providing communication including particular achievements in Last Mile Technology. This thesis focuses on the end point of the communication i.e. household applications. It analyzes the characteristics of power lines in a household in order to develop a channel model suitable to simulate its behavior for as high-speed data transmission as possible. Such channel characterization is a fundamental step toward designing efficient high-speed communication systems in power distribution networks. In order to estimate the overall communication system behavior, all of its parts are modelled as sub models. The idea behind channel modelling is very straight forward i.e. in a system all of its parts except the channel are supplied with their performance record by their manufacturer. Once the channel characteristics are known, the most suitable system components can be included in the system for a particular application. The channel model presented is also the key to design PLCC compatible modems, transmitter and receivers etc. In this thesis the exchange of data/information among the rooms of a house is the purpose for which power line carrier communication channel has been modeled. The model takes advantage of two port network model along with transmission line theory of power lines. The thesis work primarily concentrates upon attenuation and bandwidth for the modeled channel. Effect of physical parameters like cable diameter, separation between cables and length of cable on the channel’s bandwidth has been included in simulation results.

ORGANIZATION OF THESIS

The first chapter introduces the Power Line Carrier Communication, its types, advantages, disadvantages and applications. It also gives an idea about bandwidth, model, modelling approaches and need of modelling. The second chapter discusses the regulatory constraints, standards and protocols associated with Power Line Carrier Communication. The third chapter tells about the research work that has already been carried out in the area of Power line channel modelling. The fourth chapter states the problem definition and gives the detailed description of proposed solution along with implementation through simulations. The fifth chapter shows the results obtained in the form of simulated graphs and discussion over the results. And in the sixth chapter thesis is concluded with future scope of research.

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LIST OF ABBREVIATIONS

PLCC	Power Line Carrier Communication
PLC	Power Line Communication
PLN	Power Line networking
OFDM	Orthogonal Frequency Division Multiplex
GMSK	Gaussian Minimum Shift Keying
FSK	Frequency Shift Keying
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
COFDM	Coded Orthogonal Frequency Division Multiplexing
SSB	Single Side Band
OFDM	Orthogonal Frequency Division Multiplex
FFT	First Fourier Transform
DAB	Digital Audio Broadcast
DVB	Digital Video Broadcast
WLAN	Wireless Local Area Network
GMSK	Gaussian Minimum Shift Keying
MSK	Minimum Shift Keying
BFSK	Binary Frequency Shift Keying
CPSK	Coherent Frequency Shift Keying
DPSK	Differential Phase Shift Keying
ASK	Amplitude-Shift Keying
AM	Amplitude Modulation
PM	Phase Modulation
BPLC	Broadband Power Line Communications
RF	Radio Frequency
UTP	Unshielded Twisted Pair
CENELEC	Comité Européen de Normalisation Électrotechnique
EN	European Standard
DIN	Deutsches Institut für Normung

CSMA/CA	Carrier Sense Multiple Access/ Collision Avoidance
AC	Alternating Current
UPB	Universal Power line Bus
CPU	Central Processing Unit
NEK	Network Encryption Key
MDU	Multi-Dwelling Units
DES	Digital Encryption Standard
OSI	Open Systems Interconnection
DCSK	Differential Code Shift Keying
FCC	Federal Communications Commission
ARIB	Association of Radio Industries and Businesses
ECC	Error Correction Code
CRC	Cyclic Redundancy Check
EIA	Electronic Industries Alliance
CEBus	Consumer Electronic Bus
CAL	Common Application Language
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
MATLAB	Matrix Laboratory
IEEE	Institute of Electrical and Electronics Engineers
CPD	Cumulative Probability Distribution
LV	Low Voltage
MV	Medium Voltage
HV	High Voltage
LAN	Local Area Network
TEM	Transverse Electromagnetic
PVC	Polyvinyl Chloride
VDE	Verband der Elektrotechnik , Elektronik und Informationstechnik

CHAPTER 1
INTRODUCTION

Power Line Carrier Communication (PLCC) refers to transmitting information data using power lines as the communication media. Power Line Carrier Communication is also called Power Line Communication (PLC), Mains Communication, Power Line Telecoms (PLT), Power Band or Power Line networking (PLN) [1]. The communication signal is transmitted from one communication node to another through a physical path called Communication Channel. Power-line communication is basically propagation of information carrying electrical signals over power-line to be utilized as a channel.

In power line carrier communication a high frequency signal is superimposed on 50 Hz electrical signal. The idea is to accomplish transmission at low energy levels. This high frequency signal is conveyed, acknowledged and decoded by means of the power infrastructure. Thus the PLCC transmitter and receiver are positioned on the same electrical network for the particular communication. At the PLCC receiver side a coupler is integrated to eliminate low frequency components from the signal of interest. PLCC network is a kind of telecommunications network in cooperation with electrical supply network.

1.1 Communication System Model

The communication system is an arrangement designed specifically so as to exchange digital information between two locations at as high bit rates as feasible. The information is preserved in a sequence of binary digits and communicated over a channel that may have noise and interfering signals along it. A simplified model of digital communication system is shown in Figure 1.1.

1.1.1 Source

The information originates from any source that could give analog or digital data to be transmitted. If the source provides information in analog form then an analog to digital converter must be placed ahead of transmitter.

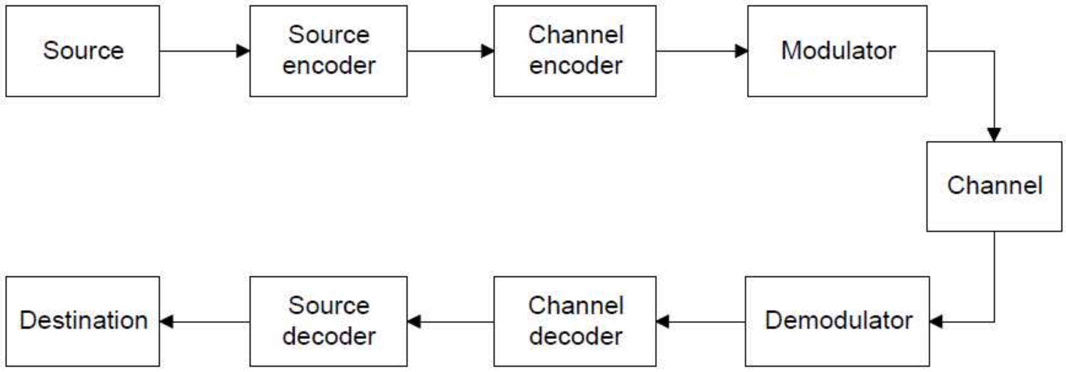


Figure 1.1: A Simplified Model of Digital Communication System.

1.1.2 Source Encoder

The function of source encoder is to compress data if possible so as to minimize the total number of bits to be transmitted over the channel. The source encoder produces data at a specific information bit rate and this data is conveyed over the channel. Bit error probability is defined as the probability that a bit is incorrectly recognized at the receiver end. The bit error probability is higher for a communication with noisy channel.

1.1.3 Channel Encoder

Channel encoder adjoins extra control bits to the data to be transmitted. For consistent transmission of high-quality voice and digital data, error rate must be awfully small. The more redundant the data is, the more it can be compressed. This redundancy is increased by inserting channel encoder such that bit error probability can be reduced.

1.1.4 Modulator

The modulator superimposes information-carrying signal over carrier frequency. At this stage converts the stream of bits into an analog signal that the channel can transmit without upsetting its information carrying characteristics.

1.1.5 Channel

The communication signal travels from modulator to receiver through a physical path called Communication Channel. Any physical medium, such as coaxial cable, air, water or telephone wires might work as a communication channel depending upon the communication purpose and location.

As already discussed characteristics of the channel are important to know because these parameters directly affect the performance of the communication system.

1.1.6 Demodulator

The demodulator acknowledges the waveform transmitted by the transmitter and converts the analog information again into the coded bit stream of data.

1.1.7 Channel Decoder

Channel decoder uses the added redundancy to detect and perhaps correct the error carried by the bit stream all the way through the channel. If it is not tolerable to extract information up to achieved bit error rate then more redundancy can be added. Thus addition of redundancy depends upon the amount of correction looked for but is in addition adjusted according to the channel characteristics.

1.1.8 Source Decoder

At the receiver end the source decoder decompresses the bit stream such as an exact replica of the information could be retrieved. While lossless data compression is practically difficult, a lossy data compression results in a distorted copy of original information signal. If the received sequence is required to be an exact replica of the transmitted stream then the degree of compression can be decreased.

1.2 The Power-Line as a Communication Channel

Figure 1.2 is given below, that shows a Digital Communication System utilizing the power-line as a communication channel.

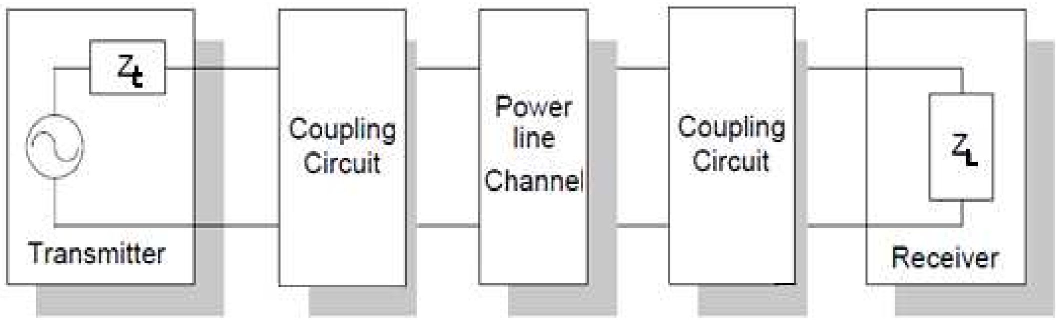


Figure 1.2: Power Line as Communication Channel in Communication System.

The leftmost block is identical to the transmitter of the digital communication system as well as rightmost block works as the receiver. The output impedance ‘Z_t’ of the transmitter and the input impedance ‘Z_L’ of the receiver are very important parameters in top-down modeling of the power line communication. For a typical PLC system, in order to improve communication performance, the transmitter power might be enhanced.

1.2.1 Coupling Circuit

This block couples digital communication system to electrical lines. Basically it consists of a set of filters so that none of the undesirable frequencies enter certain parts of the system. There are two purposes of introducing a coupling circuit at the power line interface:

- It prevents the system equipments damage from 50 Hz power distribution signal.
- It confirms that the major part of the received/transmitted signal resides within the frequency band allowed for communication.

1.3 Frequency and Modulation

Researchers propose the use of 1-30 MHz for power line carrier but this whole range can not be utilized, this will be discussed in later sections.

1.3.1 Carrier Frequency

Carrier frequency range is 50- 500 kHz. Carrier frequency includes voice signal, protection and the pilot frequency signal within its specified range:

1.3.1.1 Audio Frequency

Generally, the information is in range of audio frequency. The conversion/compression of voice signal is done within the 300Hz to 4000Hz range and then it is mixed within the carrier frequency.

1.3.1.2 Pilot Frequency

The pilot frequency is by and large a reference signal that is sent along with the information signal for supervision or synchronization purposes.

1.3.1.3 Protection Frequency

Sometimes it is desired to transmit more than one reference signal for failure detection, thus protection frequency signal can also be propagated in addition to pilot frequency signals.

1.3.2 Modulation

Amplitude modulation is commonly applied in power line communication systems. Several other modulation techniques also exist e.g., spread-spectrum [2], Orthogonal Frequency Division Multiplex (OFDM) [3], Gaussian Minimum Shift Keying (GMSK) [4], Frequency Shift Keying (FSK) [2], Phase Shift Keying (PSK) [2] and Quadrature Amplitude Modulation (QAM) [2]. Out of these all modulation techniques Coded Orthogonal Frequency Division Multiplexing (COFDM) is mostly used due to its ease of implementation [5].

1.3.2.1 Single Side Band (SSB)

Although Single Side Band (SSB) modulation lack in some areas of performance including low communication speed, feeble anti-interference facility, small spectral efficiency still it is being employed in traditional PLC Communication. Because it does not meet the data requirements in the present scenario hence it is not in demand now days.

1.3.2.2 Orthogonal Frequency Division Multiplex (OFDM)

There is no trouble to accomplish modulation or demodulation of OFDM by applying the First Fourier Transform (FFT) on digital signal processors. Applications of OFDM in power line communication include Digital Audio Broadcast (DAB), (DVB) and Wireless Local Area Network (WLAN). While considering the low voltage distribution power line, 14Mbps data transmission speed intended for the internet connection can be achieved.

1.3.2.3 Coded Orthogonal Frequency Division Multiplex (COFDM)

The digital power line communication system based on COFDM modulation avails the data compression in addition to data coding to process the signals, and then transmit the data with OFDM modulation over the power lines. It can attain over 1Mbps data transmission speed in the available frequency band of PLC Communication System.

1.3.2.4 Gaussian Minimum Shift Keying (GMSK)

Gaussian minimum shift keying is a modulation technique in which a continuous phase frequency shift keying is used; it is a digital modulation technique. This modulation technique is similar to Minimum Shift Keying(MSK) but in GSMK digital information is shaped with Gaussian filter before it is processed to a frequency modulator, this is done in order to reduce sideband power due to which outer band interference between different signal carriers in adjacent frequency channels. The main function of Gaussian Filter is that it improves the modulation memory in the system but also results in intersymbol interference.

1.3.2.5 Frequency Shift Keying (FSK)

Frequency shift keying (FSK) is one of the frequency modulation techniques. In FSK the information which is in form of digital data is sent via discrete frequency variations of a carrier signal. The simplest FSK is Binary FSK (BFSK). BFSK exactly implies to pass on binary (0s and 1s) sequence by making use of a pair of discrete frequencies. Here the '1' is known as the mark frequency and the '0' is known as the space frequency.

1.3.2.6 Phase Shift Keying (PSK)

Phase-shift keying (PSK) is a modulation technique in which data is conveyed by changing or modulating, the phase of a reference signal (the carrier wave). Other digital modulation schemes use a finite number of distinct signals to represent digital data. PSK uses a finite number of phases; each assigned a unique pattern of binary digits. Usually, each phase encodes an equal number of bits. Each pattern of bits forms the symbol that is represented by the particular phase. The demodulator, which is designed specifically for the symbol-set used by the modulator, determines the phase of the received signal and maps it back to the symbol it represents, thus recovering the original data. This requires the receiver to be able to compare the phase of the received signal to a reference signal such a system is termed coherent (and referred to as CPSK).

1.3.2.7 Differential Phase Shift Keying (DPSK)

Alternatively, instead of using the bit patterns to set the phase of the wave, it can instead be used to change it by a specified amount. The demodulator then determines the changes in the phase of the received signal rather than the phase itself. Since this scheme depends on the difference between successive phases, it is termed Differential Phase-Shift Keying (DPSK). DPSK can be significantly simpler to implement than ordinary PSK since there is no need for the demodulator to have a copy of the reference signal to determine the exact phase of the received signal (it is a non-coherent scheme).

1.3.2.8 Quadrature Amplitude Modulation (QAM)

Quadrature amplitude modulation (QAM) is both an analog and a digital modulation scheme. It conveys two analog message signals, or two digital bit streams, by changing (modulating) the amplitudes of two carrier waves, using the Amplitude-Shift Keying (ASK) digital modulation scheme or Amplitude Modulation (AM) analog modulation scheme. These two waves, usually sinusoids, are out of phase with each other by 90° and are thus called Quadrature carriers or Quadrature components, hence the name of the scheme. The modulated waves are summed, and the resulting waveform is a combination of both Phase-Shift Keying (PSK) and Amplitude-Shift Keying (ASK), or in the analog case of Phase Modulation (PM) and amplitude modulation. In the digital QAM case, a finite number of at least two phases and at least two amplitudes are used. PSK modulators are often designed using the QAM principle, but are not considered as QAM since the amplitude of the modulated carrier signal is constant. QAM is used extensively as a modulation scheme for digital telecommunication systems.

1.4 Types of PLCC Systems

The PLCC systems are broadly categorized in three types:

1. Low Voltage
2. Medium Voltage
3. High Voltage

1.4.1 Low Voltage

The low voltage power line network is a new set-up for providing an access to high-speed transmissions. The model of Broadband Power Line Communications (BPLC) is a feasible mode to build an in-house communication network or to access the internet. First of all, it will be beneficial to know the typical distribution network structure and topology. The topology of the typical low voltage network is given below in Figure 1.3. The supply lines of 220/380V low-voltage supply network begin at a transformer station and then extend over 250 meters, generally [6].

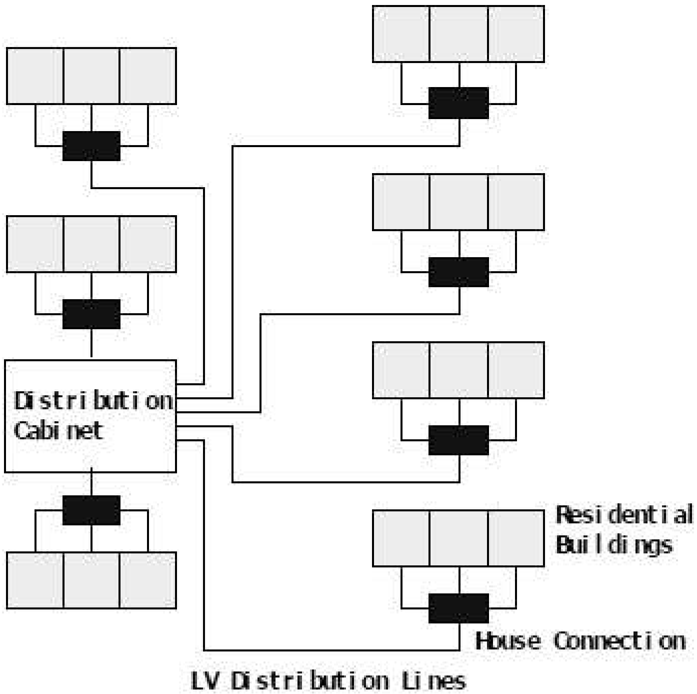


Figure 1.3: Topology of the typical Low Voltage Distribution Network.

For example, up to twelve supply lines can lead out from the transformer station and every supply line can feed up to 30 residential connections. The network can meet all requirements of home automation and management system.

Data broadcast over power lines begins after the Low Voltage side of the distribution transformer, which travels up to the customers' building through Low Voltage network. The Low Voltage electrical network has become the most attractive medium for high-speed digital communication down to an ever-increasing demand as a result of the progress in communication and information technologies. The Low Voltage network is an extensively spread network with the distribution transformer secondary as the central node and many loads connected in parallel. In contrast to the other wired communication mediums, the power line arrangement was optimized mainly for 50 or 60 Hz and was not intended for data transmission. Therefore Low Voltage power cables present an extremely harsh environment for high frequency signals.

1.4.2 Medium Voltage

This system is efficiently applied in distribution automation system such as remote reading meter, load monitoring, SCADA system etc. The structure of medium voltage power line carrier communication system is shown below in Figure 1.4.

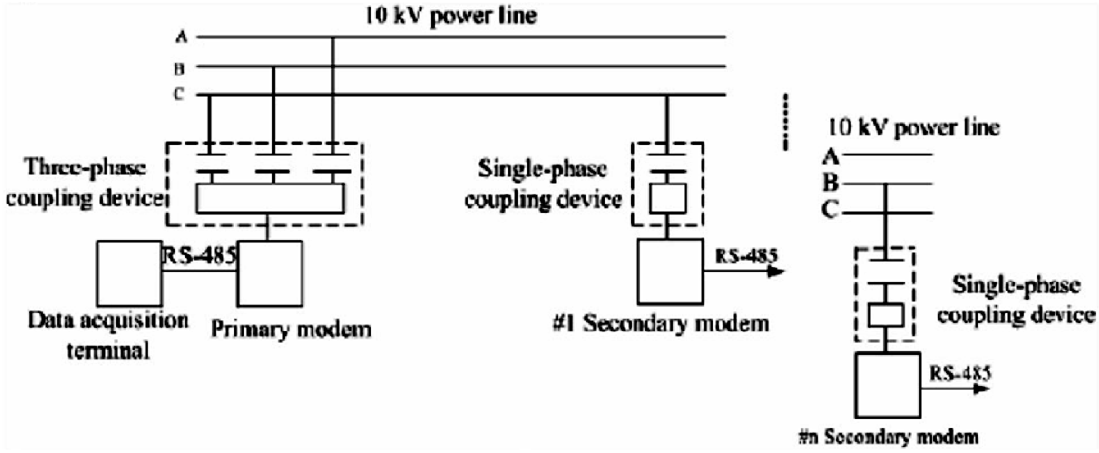


Figure 1.4: The Structure Chart of Medium Voltage PLCC System.

The medium-voltage carrier communication system consists of medium voltage power line, data acquisition terminal, coupling equipment and carrier modem as it main system components. Electric Substation comprises data acquisition terminals, remember unit and clock within. It can read meters automatically and remember the data for the time being by the means of RS-485 bus wire and complete data transmission with the centre substation.

Data transfer may be also possible through optical cable or phone line at the same time. The coupling device has coupling capacitance and filter. The electric substation carrier modem feed the signals in the mode of one to N i.e. inside the electric substation, the main modem communicate with a number of second modems at the bus line [7]. The Carrier Modem has the following two divisions:

1. Main Modem i.e. Electric Substation Carrier Modems
2. Second Modem i.e. Distributing Point Carrier Modems

Medium voltage power line carrier is economical and practical communication technology for 10kV distribution electrical line. Medium voltage power line carrier communication system is a well-known method for communicating Radio Frequency (RF) signals over electrical lines. It is mainly used within the automation reading and collecting data of all kinds of meters, the management of the user's demand, the load automation monitoring and switching, and the monitoring of features of electric power supply, the level of electric voltage, the disturbance and the harmonic wave in the far end.

1.4.3 High Voltage

A High Voltage power line carrier system consists of three distinct components. They are the terminal assemblies, the coupling & tuning equipment and the high voltage system itself. Coupling information signals to power line through interfacing circuits is a difficult task because power line and the communication system operate at two distinct boundaries i.e. very low frequency and high power for the power line and very high frequency and very low voltage and current levels for communication channel.

Coupling to power-line conductors are accomplished by using high voltage coupling capacitors to pass the carrier signals, while blocking 50 Hz power from the carrier equipment. The coupling circuit must be designed such that it is capable to withstand the high power at power line system as well as capable to prevent any damage being done to the electronic side of the communication system. At the same time it must be reliable enough to make certain that data bits are transported on to the power line very correctly.

There are some draw backs of high voltage PLCC including the expense of coupling and isolation components. Isolation is required because several independent PLCC channels are used on each line section of a large network. Since line sections are joined at substation buses, there is a possibility for mutual interference between PLCC signals. High levels of isolation between channels on the same frequency are difficult to provide across substation buses. Transmitting electricity at high voltage reduces the fraction of energy lost to resistance. For a given amount of power, a higher voltage reduces the current and thus the resistive losses in the conductor.

At extremely high voltages, more than 2 M V between conductor and ground, corona discharge losses are so large that they can offset the lower resistance loss in the line conductors [8]. The amount of power that can be sent over a transmission line is limited. The origins of the limits vary depending on the length of the line. For a short line, the heating of conductors due to line losses sets a thermal limit. If too much current is drawn, conductors may sag too close to the ground, or conductors and equipment may be damaged by overheating.

1.5 Advantages and Disadvantage of Power Line Communication

There are always pros and cons for applicability of a system. One should carefully go through these factors before implementation of the particular system. The knowledge of advantages and drawbacks helps in accepting and designing the desired technique. The acceptance and system design are generally application oriented. Given below are the benefits and inconvenience by using power line carrier communication.

1.5.1 Advantages

When we use power line network as a communication channel there are a number of advantages. The power network reaches every socket in our homes as it is the most pervasive network in the world. The power line network has excellent geographical coverage and very good performance characteristics as it uses existing cable infrastructure for both communication and power which makes it an independent communication network in the world. In power line communication network one of its main advantages is that its cost efficient as it makes use of existing wires and cables already installed in our homes and no further cost has to be spent on installation of new cables, hence it is a substitute for wireless and cable communication. It can be installed anywhere in any home or place without any further cost on cables and installation and it can even reach remote places where communication has not reached but electricity is present. Hence it is a very good solution for communication applications especially in backward places and villages.

1.5.2 Disadvantages

Everything that has Advantages also has certain Disadvantages and same is the case with Power Line Communication. In power line communication the parameters such as noise, impedance and attenuation, are unpredictable and can change with time, frequency and place which does not happen in case of wired communication mediums such as coaxial cables and Unshielded Twisted Pair (UTP). Certain factors like Installation and high performance in case of power line communication are dependent on various architectures of the electrical network being used and Interoperability problems with different kind of equipments is also a main disadvantage of power line communication. Power line communication does not have a set of standards and guidelines as well as a price at which it can be used.

Power line communication needs high frequency current lines which can operate at 50-60 Hz to 400 Hz frequency and one of the main drawbacks is the legal restrictions on frequency bands which limit data rates, contaminated noise is also unreliable. Power Loss in Power line communication is directly proportional to the square of current, and also proportional to distance. But in case of Low Voltage networks channels they are usually hostile, unusual and unpredictable as the fact that they are designed electrical energy transmission and not communication purposes.

1.6 Applications of Power Line Carrier Communication

Companies used Power Line Communication to maintain power grid due to past low data rate communication needs. High data-rate communication over low-tension lines is one of the major applications in new technologies. Power Line Carrier Communication offers symmetric as well as two way communication along with a permanent connection. Load management and meter reading from a distance are the two Primary motivations for Power line communications in future. In Automatic Meter Reading electronic data that is the meter reading is transmitted over power lines from a distant place back to the substation where the reading has to be noted, then the reading is relayed to a central computer in the utility's main office. Hence this would be considered a type of fixed network system as in this system the network being the distribution network which the utility has built in order to maintain the delivered electric power. Such kinds of systems are mainly used for electric meter reading. Even at some places providers have interfaced water and gas meters to feed into a Power Line Communication type system. The Power Line Carrier Communication applies much higher frequencies than earlier and is also responsible for substantially reduces the signal levels. . Most modern Power Line Carrier Communication systems operate with a carrier frequency of 1MHz to 30MHz. Power Line Carrier Communication (PLCC) is also used in home entertainment and Internet home appliances and its one of the major applications is telecommunication, tele-protection and tele-monitoring between electrical various substations through high voltages power lines operating at 110kV, 220kV, 400kV. In Power line communication the mains wiring is used for data communication as mains wiring network is used in nearly every house, hence the installation expenses for power line communication network involved will be reduced, compared to other communication systems. Due to these applications power line communication results in a very good alternative for the automation technology, especially in case of domestic applications. In today world power-line-communication is being used for many applications to control various systems such as street lighting or energy management systems. In homes the so called "baby-phones" are very popular in which power line communication is used in which low quality analogue voice signals is transmitted through a 230V mains wiring. In comparison to the old analogue systems used for communications, digital data which is transferred using the power-line as communication media is a very useful alternative for domestic applications, particularly for devices which are already connected to the mains (e.g. washing machines or refrigerators, linked together for energy management). Power line communication saves the biggest part of installation costs if it is used in buildings where electric wiring is already present hence no need for wiring separately for communication. Hence power line communication meets the customers' needs for low cost. Indoor power line communication should not be mixed with outdoor power line communication as both are different from one another regarding the availability of frequency bands and the maximum signal levels. The indoor power line communication is capable to transmit information at a rate of 2400bps (bits per second) at a very low cost. For domestic applications this rate of data transmission is good enough as in most of the cases in domestic applications the devices have to transmit only control signals such as on/off, dimming values etc.

1.7 Introduction to Model

A model is a simplified conceptual depiction of the complex reality, phenomena and physical processes. The modeling attempts to construct a proper system in a logical way, such as the reality is just an interpretation. Models that are delivered in software allow researchers to apply computational power towards simulation, visualization, manipulation and gain perception about the entity, phenomenon or process under characterization. Now, a system may contain software components, hardware components or both and the interconnections of these components. System modelling is planned to assist in developing, analyzing and maintaining large systems. A model can improve reliability and decrease development cost by making it easier to understand systems before realizing it in real.

1.7.1 Modelling as a Substitute for Direct Measurement and Experimentation

Models are typically used when it is either impossible or impractical to create experimental conditions in which scientists can directly measure outcomes. Although direct measurement of effects under controlled conditions will always be more accurate than modeled estimates of the effects. When predicting outcomes, models use assumptions, while measurements do not. As the number of assumptions in a model increases, the accuracy and relevance of the model diminishes. Still it is always better to have something over nothing.

In addition to this models and simulations help us to design an experimental setup best suitable for the application. Modelling minimizes the risk of experiment failure to great extent because a model is more than just a theory where outcomes can be seen in form of model simulations. The model can then be verified with the actual measurements later.

1.7.2 Modelling Approaches

In modeling approaches there are basically two important factors that affect the models one being the model parameters and another modeling algorithms. The main function of these two factors is that with the help of these two factors one can determine the accuracy and reliability of the models. The modeling techniques depending upon the methods of obtaining the above model parameters can be classified into two different approaches the bottom up approach and the top down approach [9].

In the case of top down approach it is easy to implement as it requires a small amount of computation as in top down approach the modeling parameters are obtained from measurements. As in this approach modeling parameters are obtained through calculation and measurement hence this method is prone to measurement errors. Whereas on the other hand the bottom up approaches in which we start from theoretical derivation of model parameters. As this bottom up approach compared to the top down approach requires more computational efforts but it clearly tells us the relationship between the model parameters and the network behavior. Because in this approach all the parameters are formulated hence it is more versatile and flexible, making this approach easy to predict whether should there be any change in system configuration if there is any change in transfer function.

The Algorithm of the above approach is used to achieve the modeling in time domain or in the frequency domain. The power line channel in the time domain is regarded as the multipath environment and in order to represent this physical characteristic an echo model is developed. This type of modeling is simple to implement if it is implemented in the top down approach, but in the case of bottom up approach, it is based on the approximation that the backward reflections are negligible from impedance discontinuities and even the echo model also becomes complex in case when many branches are connected together at a common joint.

The network in the case of frequency domain modelling is regarded as a composition of a number of cascade distributed portions. Therefore the whole network behavior can be described based on the scattering matrices or the transmission matrices of the cascaded portions. All the signals reflected from the discontinuities are considered in case of frequency domain modeling, regardless of the complexity of the network, this is one of the major advantages of frequency domain modeling.

1.8 Bandwidth

The frequency content of the signal on the communication channel is of great significance. The frequency interval used by the communication system is called bandwidth [2]. Bandwidth is written as 'BW' or 'Δf' and measured in Hertz. For a particular communication system, the bandwidth required is proportional to the data rate. As a consequence a high data rate needs a vast bandwidth for a predetermined technique. If the bandwidth is increased as a multiple of n then the data rate also increases n times the earlier data rate. It has already been discussed that bandwidth is a limited and precious resource and the bandwidth is often constricted to a certain small interval. This puts a restriction on the communication system to communicate within the assigned bandwidth.

In signal processing and control theory the bandwidth is the frequency at which the closed-loop system gain drops 3 dB below peak. In basic electric circuit theory when studying Band-pass and Band-reject filters the bandwidth represents the distance between the two points in the frequency domain where the signal is 0.707 of the maximum signal amplitude (half power).

For analog signals bandwidth is the width of the frequency range in which the signal has nonzero Fourier Transform. Because this range of nonzero Fourier Transform might be very extensive, this definition is relaxed such that the bandwidth is defined as the range of frequencies where the signal's Fourier Transform has a power above a definite threshold, generally half of the maximum value or −3 dB [10]. The word bandwidth is concerned to signals as described above, but it could also apply to systems, for example filters or communication channels.

To say that a system has a certain bandwidth means that the system can process signals of that bandwidth. A baseband bandwidth is synonymous to the upper cutoff frequency, i.e. a specification of only the highest frequency limit of a signal. A non-baseband bandwidth is a difference between highest and lowest frequencies. The fact that real baseband systems have both negative and positive frequencies can lead to confusion about bandwidth, since they are sometimes referred to only by the positive half, and one will occasionally see expressions such as B = 2W, where 'B' is the total bandwidth, and 'W' is the positive bandwidth.

CHAPTER 2
PLCC REGULATIONS AND STANDARDS

Power lines are leaky i.e. there is a radiation of high-frequency electromagnetic signals. Radiation emission of power lines is the major debatable concern now days. The bandwidth and bit rate are proportionally interrelated, thus in order to achieve high bit rates a large bandwidth is required. The troublesome issue is that parts of the entire frequency band are allocated to other communication systems. The communication systems using these frequencies must not interfere with power lines as well as the PLCC must not disturb their communications. Although PLCC lacks standardization yet there have been some laws and restrictions so that a companionable communication system can be realized over existing electrical lines.

2.1 CENELEC Regulatory Standard

In Europe the allowed bandwidth is regulated by the CENELEC standard. The standard only allows frequencies between 3 kHz and 148.5 kHz. This puts a hard restriction on power-line communications and might not be enough to support high bit rate applications, such as real-time video, depending on the performance needed. The European Committee for Electrotechnical Standardization in Brussels (CENELEC) published the standard EN 50065-1, "Signalling on low voltage electrical installations in the frequency range 3 kHz to 148.5 kHz" [11]. The EN 50065-1 regulates all power line signalling within the frequency range 3 kHz to 148.5 kHz and it has been adopted by the German Electrotechnical Commission in DIN and VDE as DIN-EN 50065-1, classification VDE 0808, as well as by many other European national committees.

The frequency range is subdivided into five sub-bands. The first two bands (3-9 and 9-95 kHz) are limited to energy providers and the other three are limited to the customers of the energy providers. In addition to specifying the allowed bandwidth the standard also limits the power output at the transmitter. Broadly four different frequency bands are specified:

- The A-band (3 kHz - 95 kHz) is reserved for power companies.

- The B-band (95 kHz – 125 kHz) can be used by all applications without any access protocol.
- The C-band (125 kHz – 140 kHz) is reserved for home network systems. A mandatory access protocol (CSMA/CA = Carrier Sense Multiple Access/ Collision Avoidance) facilitates the coexistence of different incompatible systems in the same frequency band.
- The D-band (140 kHz - 148.5 kHz) is specified for alarm- and security-systems without any access protocol.

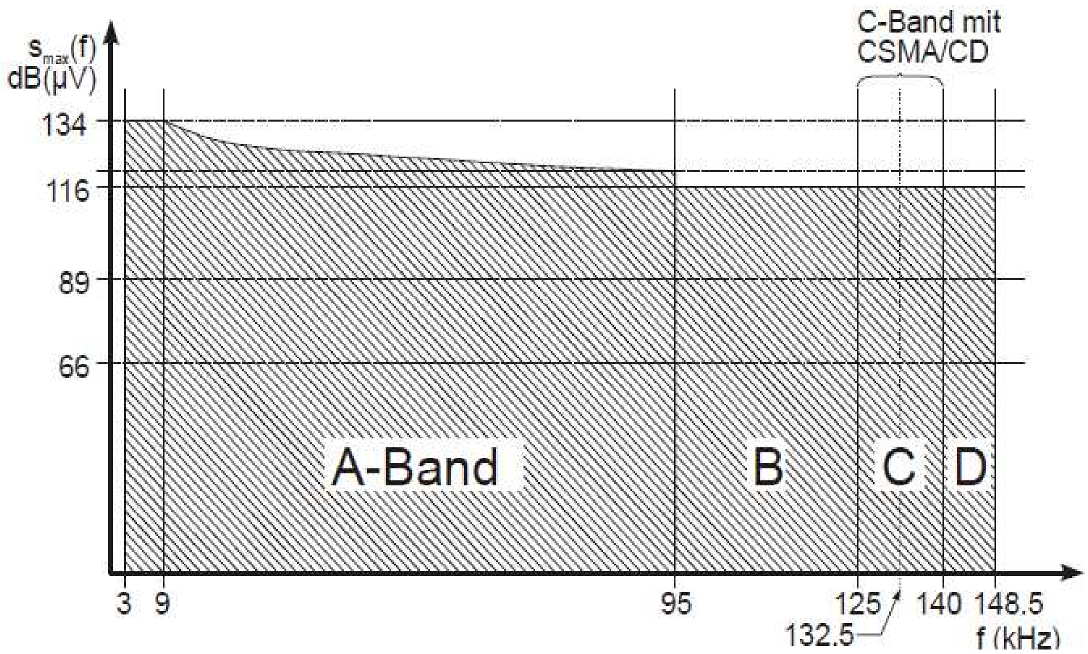


Figure 2.1: Maximum Output Level in Frequency Range 3 kHz-148.5 kHz.

For all four frequency bands, a maximum output level is required by EN50065-1 for the signal transmission via power-line. This maximum output level is given above in Figure 2.1. For the use in home network systems, the C-band with a maximum level of 116 dB (μ V) is the best choice, because a media access protocol is required. The maximum output level has to be measured by a peak level detector and a given receiver circuit during a period of one minute.

Additionally, the EN 50065-1 defines noise levels for all frequency bands, mandatory for any electrical appliance connected to the mains in Europe. Thus, the potential parasitic influence by disturbances is decreased to a minimum. Recent research has suggested the use of frequencies in the interval between 1 and 20 M Hz [12] [13].

2.2 X10 Standard

X10 was developed in 1975 by Pico Electronics of Glenrothes, Scotland so that it can allow remote control of home devices and appliances. X10 is an international industry standard used for communication among electronic devices. It used for home automation also known as domestics, which primarily uses power line wiring for signalling and control, where the signals involve brief radio frequency bursts representing digital information [14]. A wireless radio based protocol transport is also defined. It was the first general purpose domestic network technology which is most widely available.

2.2.1 Working of X10 protocol

A 120 KHz, 1ms burst is transmitted near the zero crossing of the 50/ 60Hz Alternating Current (AC) signal. Two crossings are required to form a single bit. To generate"1" a burst at the first crossing is needed and none at the second. Things would get out of sync very fast if some way of starting the whole data packet is not there. A special start sequence is used after which, the next 9 bits represent the actual data being transmitted. The first 4 bits are the house codes which are represented by letters on the actual devices to make it easier on the consumer as shown in Table 2.1.

Table 2.1: House Codes used by X10 Protocol.

A	0110
B	1110
C	0010
D	1010
E	0001
F	1001
G	0101
H	1101
I	0111
J	1111
K	0011
L	1011
M	0000
N	1000
O	0100
P	1100

After the house code, the next 5 bits represent the device code or function to perform as shown in Table 2.2 and 2.3 respectively. The last bit is actually used to indicate that the device is to perform a function if the bit is 1. The complete message from start to finish is sent twice for redundancy.

Table 2.2: Device Codes used by X10 Protocol.

1	01100
2	11100
3	00100
4	10100
5	00010
6	10010
7	01010
8	11010
9	01110
10	11110
11	00110
12	10110
13	00000
14	10000
15	01000
16	11000

Table 2.3: Function Codes used by X10 Protocol.

All Units Off	00001
All Lights On	00011
On	00101
Off	00111
Dim	01001
Bright	01011
All Lights Off	01101
Extended Code	01111
Hail Request	10001
Hail Acknowledge	10011
Preset Dim	10101
Extended Data	11001
Status On	11011
Status Off	11101
Status Request	11111

In reality the X10 specification calls for three pulses to be transmitted to make the X10 compatible with a 3-Phase distribution system. The 2nd Pulse is sent 2.778ms after the zero crossing and the 3rd pulse is sent 5.556ms after the zero crossing [15].

In the 60 Hz AC current flow, a bit value of one is represented by a 1 millisecond burst of 120 kHz at the zero crossing point (nominally 0°, but within 200 microseconds of the zero crossing point), immediately followed by the absence of a pulse. A zero value is represented by the absence of 120 kHz signal at the zero crossing point (pulse), immediately followed by the presence of a pulse. All messages are sent twice so that there is no false signaling. Allowing for retransmission, line control, etc, makes the technology confined to turning devices on and off or other very simple operations [16].

Every data frame transmitted always begins with a start code of 1110 in order to provide a predictable start point immediately after which, a house code (A–P) appears, and then comes a function code which may specify a device code (1–16) or a command code, the selection between the two modes being determined by the last bit where 0=unit number and 1=command. One start code, one letter code, and one function code is known as an X10 frame which represent the minimum components of a valid X10 data packet. Each frame is sent twice in succession so that receivers understand it over any power line noise for purposes of redundancy, reliability, and to accommodate line repeaters. Whenever the data changes from one address to another address, from an address to a command, or from one command to another command, the data frames must be separated by at least 6 clear zero crossings (or "000000") which resets the device decoder hardware.

When the system is installed, each controlled device is configured to respond to one of the 256 possible addresses (16 house codes × 16 device codes); and reacts to commands specifically addressed to it, or possibly to several broadcast commands. For example, the protocol may transmit a message that says "select code A3", followed by "turn on", which commands unit "A3" to turn on its device. Several units can be addressed before giving the command, allowing a command to affect several units simultaneously. Like, "select A3", "select A15", "select A4", and finally, "turn on", causes units A3, A4, and A15 to all turn on.

There is no restriction (except possibly consideration of the neighbors) that prevents using more than one house code within a single house. The "all lights on" command and "all units off" commands will only affect a single house code.

2.3 Universal Power line Bus (UPB) Protocol

UPB is a protocol for communication among devices used for home automation. It uses power line wiring for signaling and control. UPB was developed by PCS Power line Systems of Northridge, California and released in 1999. UPB has an improved transmission rate and higher reliability. While X10 has reported reliability of 70-80%, UPB reportedly has a reliability of more than 99%. Household electrical wiring such as Romex or BX is used to send digital data between UPB devices [17].

The UPB communication method consists of a series of precisely timed electrical pulses (called UPB Pulses) that are superimposed on top of the normal AC power waveform (sine wave). These UPB Pulses can be easily detected and analyzed by UPB devices which can pull out the encoded digital information from them. UPB Pulses are generated by charging a capacitor to a high voltage and then discharging that capacitor's voltage into the power line at a precise time which creates a large "spike" (or pulse) on the power line that is easily detectable by receiving UPB devices wired large distances away on the same power line.

UPB controllers range from extremely simple plug-in modules to very sophisticated whole house home automation controllers. The simplest controllers are plug-in controllers that are recommended for a moderate amount of switches and more sophisticated controllers can control more units and/or incorporate timers that perform pre-programmed functions at specific times each day. Units are also available to turn lights on and off based on external conditions. The digital data consists of an address and a command sent from a controller to a controlled device. More advanced controllers can also query equally advanced devices to respond with their status. This status may be as simple as "off" or "on", or the current-dimming level, or even the temperature or other sensor reading. Devices usually plug into the wall where a lamp, television, or other household appliance plugs in. However some built-in controllers are also available for wall switches and ceiling fixtures. These systems can execute many different timed events, respond to external sensors, and execute, with the press of a single button, an entire scene, turning lights on, establishing brightness levels, and so on.

Features and benefits provided by the UPB technology include:

- Improved communication and enhanced noise immunity for superior reliability even in the noisiest of environments.

- Swifter reaction time of switches when tapped; virtually no delay between tapping of switch and light reaction.

- Full compatibility with UPB split phase repeaters.

- Advanced Addressing that allows 250 devices per house, 250 houses per transformer that has greatly reduced the chance of overlap between houses.

- UPB switches can peacefully co-exist with other Power line carrier systems within the same home.

2.4 LonTalk Protocol

A Channel is a physical transport medium for packets. A network may be composed of one or more channels. In order for packets to be transferred from one channel to another, a device called a router or repeater is used to connect the two channels which include two transceivers to communicate between the two channels. The LonTalk protocol supports such a device in order to construct multi-media networks and optimize network loading by localizing traffic.

Channels can be configured for different bit rates to trade-offs of distance, throughput and power consumption. The maximum bit-rate is 0.25, 1.2, 2, 4, 4.9: 9 8, 19.5, 39.1, 78.1, 156.3, 312.5, 625 or 1 250 k bit/s. Channel throughput depends on the bit rate, oscillator frequencies and accuracy, transceiver characteristics, the average size of a packet, and the use of confirmations, priority, and authentication. A typical package is in the range 10 to 16 bytes long, depending on the length of the identifier as a domain, addressing mode and the size of the data field to a variable the updating of the network, or an explicit message. The maximum packet size is 255 bytes, including data, addressing, and the protocol overhead [18].

2.4.1 LonTalk Addressing

The LonTalk Addressing can be described in a hierarchal order. The hierarchy levels are given as follows:

- The top level of the hierarchy addressing is a domain. For example, separate each domain ID is used to keep the programs completely if the various network applications are implemented on a shared communication medium such as RF. Domain ID is selectable, 0, 1, 3 or 6 bytes long. A node can be a member of up to two domains.
- The second level to deal with is the subnet. There may be up to 255 subnets per domain. A subnet mask is a logical grouping of nodes from one or more channels. An intelligent router works level subnets. It determines the subnets are on either side of it, and forwards packets accordingly.
- The third level of addressing is the node. There may be up to 127 nodes per subnet. Thus a maximum of $255 \times 127 = 32{,}385$ nodes may be in a single domain. Any node may be a member of one or two domains, allowing a node to serve as an inter-domain gateway. This also allows, for example, a single sensor node to transmit its outputs into two different domains.

Nodes can also be grouped together that can span multiple subnets within a domain, a variety of transmission media, as well as different channels. Up to 256 groups can be set within a domain, and up to 64 nodes can be in a group of acknowledged or request/response service. An unlimited number of nodes may belong to a group of obscure service within a domain. A node can be a member of up to 15 groups for receiving messages. Group addressing reduces the number of bytes of the address information is transmitted with each message, and many nodes can receive a piece of information with a single message on the network.

In addition, each node carries a unique 48-bit ID assigned during manufacture which is typically used as a network address only during installation and configuration and by application programs as a unique product serial number. Nodes are addressed using one of five addressing formats given in Table 2.1.

Table 2.4: Addressing Formats of Nodes in LonTalk Protocol.

Address Specification	**Nodes Addressed**
Domain, Subnet = 0	All nodes in the domain
Domain, Subnet	All nodes in the subnet
Domain, Subnet,	Node Specific logical node
Domain, Group	All nodes in the group
Domain, Subnet, ID	Specific physical node

2.4.2 Message Services

The LonTalk protocol offers four basic types of message service. The first two service types are acknowledged end-to-end, and include the following:

- **Acknowledged (ACKD)**, where a message is sent to a node or group of nodes, and individual acknowledgments are expected from each receiver. If the acknowledgments are not all received, the sender times out and retries the transaction. The number of retries and the time-out are both selectable. The acknowledgments are generated by the network Central Processing Unit (CPU) without intervention of the application. Transaction IDs keep track of messages and acknowledgments so that an application does not receive duplicate messages.

- **Request/Response (REQUEST)**, where a message is sent to a node or group of nodes, and individual responses are expected from each receiver. The incoming message is processed by the application on the receiving side before a response is generated. The same retry and time-out options are available as with ACKD service. Responses may include data, so that this service is particularly suitable for remote procedure call, or client/server applications.

The remaining two service types are unacknowledged. They are the following:

- **Repeated (UNACKD_RPT)**, where a message is sent to a node or group of nodes multiple times, and no response is expected. This service is typically used for multicasting a large groups of nodes, a situation in which the traffic generated by all the responses would otherwise overload the network.

- **Unacknowledged (UNACKD)**, where a message is sent once to a node or group of nodes, and no response is expected. This is typically used when the highest attainable transmission rate is required, or when large amounts of data are to be transferred. The application must not be sensitive to the occasional loss of a message when using this service.

The LonTalk protocol provides duplicate message detection, and normally delivers a message to the destination application only once, even when the message has been duplicated. Duplicate packets can occur when acknowledgements and responses are lost, when packets are unintentionally overheard on open media such as RF and power line, and when using unacknowledged repeated service. Duplicate detection capability is provided by a receive transaction database in each node.

2.4.3 Authentication

The LonTalk protocol supports authenticated messages, which allow the receivers of a message to determine whether the sender is authorized to send that message. This is used to prevent unauthorized access to, or control of, nodes and their applications. Authentication is implemented by distributing 48-bit keys, one per domain, to the nodes at installation time. For an authenticated message to be accepted by the receiver, both sender and receiver must possess the same key. This key is distinct from the node's ID.

When an authenticated message is sent, the receiver challenges the sender to provide authentication, using a different random number as a challenge every time. The sender then responds by transforming the challenge, using the authentication key along with the data in the original message. The receiver compares the reply to the challenge with its own transformation on the challenge. If the transformations match, the transaction goes forward.

The transformation used is designed such that it is extremely difficult to deduce the key, even if the challenge and the reply are both known. The use of authentication is configurable individually for each network variable connection. In addition, network management transactions may optionally be authenticated.

2.4.4 Priority

The LonTalk protocol offers an optional priority mechanism to improve the response time for critical packets. The protocol permits the user to specify priority time slots on a channel, dedicated to priority nodes. Each priority time slot on a channel adds time to the transmission of every message [19].

2.4.5 Collision Avoidance

The LonTalk protocol uses a unique collision avoidance algorithm which has the property that under conditions of overload, the channel can still carry its maximum capacity, rather than have its throughput degrade due to excess collisions.

2.4.6 Collision Detection

The LonTalk protocol supports detection of collisions and automatic retransmission which allows a node to retransmit the packet much sooner than if one were to rely solely on upper layer timeouts. Packet retransmission is subject to normal media access delays.

In direct mode (i.e. differential or single-ended), collisions can be identified as early as 25% of the preamble up to the end of the package. Discovery of a collision ends normally not packet transmission. Packet transmission, however, may be terminated at the end of the preamble. To quit at the end of the preamble requires that all nodes are involved in a collision detect that a collision at the start.

2.4.7 Data Interpretation

The LonTalk protocol applies no special processing to foreign frames; they are treated as a simple array of bytes. The application program may interpret the data in any way it wishes.

2.5 Home Plug 1.0 Protocol

HomePlug 1.0 consists of a set of stations that are connected to the same AC power line and share a common Network Encryption Key (NEK). In Multi-Dwelling Units (MDUs) such as apartment buildings, Logical Networks are often in close proximity and are therefore able to receive packets from “neighbour networks”. Packets transmitted on a HomePlug 1.0 can be encrypted using a 56-bit Digital Encryption Standard (DES) key that is unique to that particular logical network, thus ensuring data privacy [20].

2.5.1 System Architecture

HomePlug is designed after the OSI-7 layers reference model [21] [22].

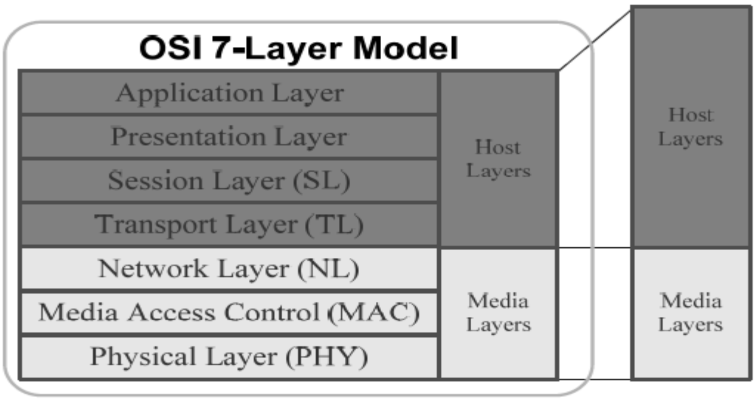


Figure 2.2: The OSI Layer Model

2.5.1.1 Physical Layer

The Physical Layer (PHY) is the first layer in the seven-layer Open Systems Interconnection (OSI) Model. It defines the electrical, mechanical, procedural, and functional specifications for activating, maintaining and deactivating the physical link between communicating network systems. These include characteristics such as voltage levels, timing of voltage changes, physical data rates, maximum transmission distances, and physical connectors. HomePlug physical layer features are given below:

- DCSK - Differential Code Shift Keying spread spectrum for extremely robust communication.
- Extremely high in-phase and cross-phase reliability (high dynamic range).
- High immunity to signal fading, various noise characteristics, impedance modulation and distortion.

- Configurable to support worldwide regulations compliance (FCC, ARIB, CENELEC A & B)
- Multiple data rate modes: SM (DCSK6, 7.5Kbps), RM (DCSK4, 5Kbps), ERM (DCSK4 with repetition code, 1.25Kbps in FCC/ARIB Bands, RM (DCSK4, 2.5Kbps) and ERM (DCSK4 with repetition code, 0.625Kbps) in CENELEC Bands.
- Frequency diversity - 3 reception Digital channels provide high immunity to interference.
- Powerful Error Correction Code (ECC) and packet detection schemes along with Adaptive packet detection
- CRC-8 for packet header and CRC-16 payload for additional reliability.
- Clock recovery algorithm for low accuracy, low cost XTAL (150 PPM).

2.5.1.2 Media Access Control Layer

The Media Access Control (MAC) sub-layer provides data services and channel access control mechanism that make it possible for many nodes and devices share the power line media and communicate without mutual interference.

MAC layer features include adaptive CSMA/CA Channel Access, Channel Access Priorities (High, Normal, Low) ,Address filtering based on Network ID & Node ID, Up to 1,023 logical networks and 2,047 nodes/network, Reliable Packet transmission & reception, Acknowledged & Unacknowledged data transmission services, Fragmentation and re-assembly of long packets - 16 fragments of 110 bytes (max. 1760 bytes per packet), Internetworking packet transmission service (to nodes on a different Network), Virtual Jamming Algorithm, Full security suite, based on AES 128-bit encryption with authentication, and packet repeating attack protection, Supports Standard (DCSK6), Robust (DCSK4) and Extremely Robust transport modes and Adaptive Rate Control.

2.5.1.3 Network Layer

The Network Layer (NL) is currently in the final stages of certification. The NL will include Internetworking and Intranetworking data services, Management services; creating logical networks, automatic routing and addressing, security, optimized overhead, Tree and Mesh Adaptive Routing as well as Secured network formation.

2.5.1.4 Host Layer

The Host Layer (HL) is also currently in the final stages of certification. One of the main goals of the standard is to ensure interoperability among devices that support the HomePlug stack from different manufactures. For example, a gateway from one manufacturer should be able to control home appliances from various companies without any special requirements from the home owner.

The Host Layer will include Transport and Session layers profiles, that provide a common description language to define devices in terms of services supported, service properties and actions, and sub-devices as well as implements device profiles and interfaces lower layers' services.

Advanced end to end communications services include:

- **Discovery** - enables devices to discover other devices and/or be discovered by other devices.
- **Binding –** enables the creation of bindings between devices, where services from different devices are bound together.
- **Controlling and Eventing –** enables remote command and control over bound device behaviour and remote monitoring of the bound device state.
- **Monitoring** – enables the query values of selected properties remotely (bound or unbound).

2.6 Consumer Electronic Bus

CEBus or Consumer Electronic Bus is the most popular PLCC systems. CEBus, also known as EIA-600, is a set of electrical standards and communication protocols for electronic devices to transmit commands and data which is suitable for devices in households and offices, for utility interface and light industrial applications.

The CEBus standard includes spread spectrum modulation on the power line which involves starting a modulation at one frequency, and altering the frequency during its cycle. The CEBus power line standard begins each burst at 100 k Hz and increases linearly to 400 k Hz during 100 microsecond duration. Both the burst (referred to as "superior" state) and the absence of burst (referred to as the "inferior" state) create similar digits, so a pause in between is not necessary [23].

A digit 1 is created by an inferior or superior state that lasts 100 microseconds, and a digit 0 is created by an inferior or superior state that lasts 200 microseconds. Consequently, the transmission rate is variable, depending upon how many of the characters are one and how many are zero; the average rate is about 7,500 bits per second. A 400 microsecond burst is an end of frame indicator and also saves time. For example, if the 32-bit destination address field has some of its most significant bits zero, they need not be sent; the end of frame delimits the field and all receiving devices assume the untransmitted bits are zero.

CEBus transmissions are strings or packets of data that also vary in length, depending upon how much data is included. Some packets can be hundreds of bits in length. The minimum packet size is 64 bits, which at an average rate of 7,500 bits per second, will take about 1/117th of a second to be transmitted and received.

The CEBus PLCC standard specifies that a binary digit is represented by how long a frequency burst is applied to the channel. For example, say at any instance, a binary “1” is represented by 100 microsecond burst, while a binary “0” is represented by a 200 microsecond burst. As a result, the CEBus transmission rate depends on the number of “0” and “1” characters that are transmitted.

The CEBus standard gives a language of object oriented controls including commands for volume up and down, temperature up one degree, etc. [7]. CEBus is a commercially owned protocol and thus its applications require registration fees. The currently commercially available PLCC systems are low capacity, relatively simple systems designed primarily for home automation.

2.6.1 CEBus Protocol Model

The CEBus protocol is also structured after the ISO/OSI seven-layer network model. Some of the layer details are given below:

- The Physical Layer performs the spread spectrum symbol encoding and decoding, recipient of the correlation, tracking, and error detection.
- Data Link Layer (DLL) implements address assignments, channel access arbitration, collision avoidance along with package confirmation services.
- Network Layer provides services for several media routing, packet segmentation and flow control.
- Application Layer consists of high level language syntax, called the Common Application Language (CAL), as a product control messages are created.

CEBus does not specify the manifestation of these protocol layers. Designers implement as much of the protocol layers as possible in embedded software to reduce recurring manufacturing costs.

2.7 Power Line Home Bus System

Power line Home bus uses line domestic power for installation is a benefit for all existing houses. Standard protocol details for power line Home bus system are described below [24]:

2.7.1 Physical Layer

The Physical Layer deals with Physical and electrical conditions in which transmission media is an AC 100v single phase power line with maximum 255 connected terminals. It is modulated by Amplitude Modulation (AM) tone burst. The power source frequency is 50 Hz for Europe and 60 Hz for America. With this frequency we send carrier frequency which range 125 k Hz or 165 k Hz on which data is transmitted with two speeds, 100 or 200 bits/second (at 50Hz) 120 or 240 bits/second (at 60Hz). The transmitting output is 100mW and 20mV is the receiving sensitivity

2.7.2 Data link layer

The data link layer consists of Link control procedure which is Carrier Sense Multiple Access with Collision Detection (CSMA/CD). They have a byte structure with no parity. Generally they have two frame formats which are shown below.

Format 1

PR	SA	DA	CC	SC	BC	DATA	FCC

Format 2

PR	SA	DA	CC	SC	HC	BC	DATA	FCC

Where PR is Priority code, SA is Source Address, DA is Destination Address, CC is Control code, SC is System code, HC is house code, BC is Byte Counter, DATA is Data (1-4 byte) and FCC is Frame Check Code.

Frame check Code performs the Error detection and the frame priority is set by four levels. For Collision detection there is bit verification for each bit period (‘0’ has priority). Home Bus Control System is a functional communications tool for the Power Line carrier Communication which is highly reliable, low in cost and compact, easy to use.

CHAPTER 3
LITERATURE REVIEW

In 2000, C.K. Lim et al. developed and implemented a test bed for high-speed PLC system. They simulated the power line environment with the worst case transient that can be generated by using impairment devices such as light dimmer circuits. It offered a controllable and repeatable power line characteristics environment to the PLC developers so that their designed PLC system can be tested and developed to a reliable system. The PLC transceiver had been designed with matching impedance of 50Hz and with capability to drive the power lines at other impedance as well. The echo canceller was implemented with the application of LNLMS algorithm because of its stability and ability to provide a fast convergence or adaptation rate to estimate the echo of the local transmitted signal. The target was to communicate data reliably over power lines at speeds of at least 1 MB with frequency ranging from 1MHz to 10MHz**.** The test bed was integrated with a power line communication channel, power line couplers, loads and impairment devices for worst case environment simulation. A method for coupling the high-frequency signal onto and from the power line was discussed. The design of digital filters for transceivers using advanced digital signal processing techniques was presented. The digital filters were used to amplify condition and recover the high-frequency signals which had been attenuated and corrupted by noise at the channel. It was specifically designed for frequency spectrum of l MHz to 10MHz with the data transmission rate of at least l Mbits/s, and for frequency spectrum of 100 kHz to 400 kHz under CEBus power line physical layer and medium specification. The hardware layout of the PLC test bed and interfacing technique with the ac power lines were described. A brief overview of a PLC system and the characteristics of power lines were discussed. The PLC transceivers using advanced digital signal processing (DSP) techniques for extracting and recovering the corrupted and attenuated receiving signals were presented [25].

In 2000, N-H. Ahn et al. presented a systematic method of probing channel characteristics and communication reliabilities of home power line communication network applied to the Internet accessed control of home appliances. The effects of the three performance deteriorating factors, i.e., additive noise, channel attenuation, and intersymbol interference, was systematically measured by applying the channel probing waveform in the frequency range from 100 kHz to 450 kHz. Probability of bit error was derived with the probed channel parameters of the signal attenuation, noise and signal-to-interference ratio read in the frequency domain. The experimental results supported the feasibility of commercially deploying of the PLC modem installed home appliances and their services for the internet accessed home automation. Also the agreement between the derived probability of bit error and the measured probability of bit error supported the validity of the proposed approach of probing home power line channel characteristics. [26].

In 2002, H. Meng et al. presented an approach to model the transfer function of the broadband Power Line Communication channel. In the approach, the power line was firstly approximated as a two-wire transmission line. The two intrinsic line parameters, the characteristic impedance and the propagation constant, were derived based on the transmission line theory. Then from the derived line parameters, an echo-based model was used to determine the transfer function for communication signals in the frequency range of 1MHz-30MHz. It was a bottom up approach. Firstly, as in the conventional bottom up approach, the two intrinsic line parameters, the characteristic impedance and the propagation constants were derived. Then the transfer function for high-frequency PLC signals was obtained using an echo-based model, which was usually used in the top down approach. Their approach had the accuracy of the conventional bottom up approach while providing simplification to the modeling algorithm. The focus of this approach was on the in-house power line laid inside metal conduit in the frequency range of 1MHz-30MHz. An echo-based model was used to determine the transfer function of the multi-branched power networks and the corresponding measurements were done to verify the derived model. Their work provided the primary line parameters for the two-wired transmission line for which the core of the cable was solid and there was no other conductor around it [27].

In 2002, M. Zimmermann and K. Dostert presented an analytic model describing complex transfer functions of typical power line networks using only a small set of parameters. The model was based on physical signal propagation effects in mains networks including numerous branches and impedance mismatching. Besides multipath propagation accompanied by frequency- selective fading, signal attenuation of typical power cables increasing with length and frequency was considered. A verification of the model at a test network, as well as its use for definition of attenuation profiles and reference channels, demonstrate the practical value of the proposed model. A model of the complex frequency response of PLC links for the frequency range from 500 kHz to 20 MHz has been derived from physical effects, namely multipath signal propagation and typical cable losses. Measurements at 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. They demonstrated that the accuracy of the model applied to a real world scenario strongly depends on the number of paths and on the exact parameter settings. For PLC-system performance analysis, simplified models with only a small number of paths representing not all the details but covering dominant effects were desirable. The parameter estimation strategy was a three-step approach. In the first step, the attenuation coefficients were determined from the attenuation profile using a single-path model with a least-squares estimator. In the next step, the number, position, and amplitude of the significant paths was derived from the impulse response by a simple peak detection approach. There work outlined a top-down strategy considering the communication channel as a black box and describing its transfer characteristics by a frequency response in the frequency range from 500 kHz up to 20 MHz by very few relevant parameters. The structure of the model was based on fundamental physical effects, which were analyzed during a great number of measurements [28].

In 2003, N. Pavlidou et al. gave an overview of the research, application, and regulatory activities like CENELEC, AMRA, EIA and IEEE on power line communications. They investigated transmission issues on the power line and illustrated that impedance was highly varying with frequency and ranges between a few ohms and a few kilo ohms with peaks at some frequencies where the network behaves like a parallel resonant circuit. They also reviewed that noise spectrum in the frequency range up to 145 kHz consists of four types of noise i.e. Colored background noise, Periodic impulse noise, Narrowband noise and Asynchronous impulsive noise. They classified the transfer function models of power lines in two categories:

hardware approach and communication approach. Several modulation techniques e.g. FSK, CDMA, OFDM, COFDM, CSMA, CSMA/CD, TDMA were discussed too [5].

In 2000, L.T. Tang et al. presented techniques for characterization of power lines in Singapore power distribution network and methodologies to extract necessary information from the measured data in 1 MHz to 10 MHz frequency range. They characterized the power line by its multipath effects. Measurements were made on the noises in actual residential power lines, which were generated from some typical electrical apparatuses used in an ordinary home. The equipment and locations used to obtain the measurements were described. The results of impulse noise measurements in typical residential power lines were presented. Statistical analyses of the measurements were presented in the form of amplitude probability distributions, pulse duration distributions, and interarrival time distributions. From the results obtained, they observed that the noise and signal attenuation of power distribution lines vary with frequency, time and location. These were caused by the rather dynamic nature of power lines and their connected loads that were changing all the time. All the results were based on measurements with and without specific electrical loads on the 230 V power line network and were measured between line and neutral conductors. The impulse noise characteristics of power distribution lines were also presented. Noise sources close to the receiver had the greatest effect on the received noise structure, particularly when the network attenuation was large. Some noise sources increased the background noise power and other increased the impulse noise power. Also, for a given transmission speed, the impulse noise width determined the number of data bits affected and its interarrival times gave an idea of the error frequency. The transfer function of the power line channel was represented by an echo model and this model was realized as FIR filter or tapped delay line and the noise spectrum was derived statistically from measurements on actual power lines. The amplitude statistics of power line noise were obtained using the Cumulative Probability Distribution (CPD) method. Channels of different characteristics were described by different numbers of paths. Each path was defined by different parameters as delay, amplitude and phase. They showed that the impedance, noise and attenuation of power lines exhibit variations with frequency, time and location as well as the power line noise was predominated by the short-wave radio signals and background noise. From the attenuation measurement obtained in the power distribution lines, due to the impedance discontinuity as source of reflection, the power line transmission had to cope with echoes and deep narrow notches in the frequency characteristics [29].

In 2004, T.E. Mhlongo and T.J. Afullo, described the power line as a communication medium and then they discussed problems encountered in the power line communication channel in terms of frequency response and noise characteristics. A transmission technique (OFDM) that avoids power line noise and uses the common modulation formats was also explained. Traffic projections were also estimated based on Brady's measurements. They presented power lime network as an alternative technology for communication in non-urban or rural areas. Since the power line network was a harsh communication medium, OFDM had proved to be the most suitable transmission technique. According to the simulation results BPSK gives the best spectral efficiency. System capacity can be increase using DQPSK (2 bits/Hz) and 16 DPSK (4bits/Hz) but the cost of a higher Bit Error Rate(BER) [30].

In 2004, H. Meng et al. approximated power line as a transmission line and the two intrinsic parameters, the characteristic impedance and the propagation constants, were derived based on the lumped-element circuit model. Using these intrinsic parameters, the transfer characteristics for an N-branch power distribution network were derived based on the scattering matrix method. The model had been verified with practical measurements conducted on actual power networks. They demonstrated that the model accurately determines the line characteristics under different network configuration as well when different household appliances were connected. They reviewed existing modeling approaches for PLC and compared their advantages and disadvantages. The model considered the type of cable used and the cable mounting method. Making use of these intrinsic parameters as the model parameters, the LV power network was then regarded as an N-branch network, which was subdivided into several cascades of smaller networks [31].

In 2004, G. A. Franklin documented power line carrier (PLC) systems used on high voltage transmission lines for protection purposes susceptible to destructive resonant conditions when excited by a harmonic source. The work expanded previous research by presenting state-space models of three common types of power line carrier systems. Frequency response models, in conjunction with harmonic analysis data, would allow PLC problems to be anticipated and addressed proactively. Therefore, the purpose of there work was to present state-space models of three common types of PLC systems: single-frequency, dual-frequency, and second order wideband systems. State-space modeling was chosen because of the generality and versatility of the models. Using a software package, such as MATLAB, the models could be used for both time-domain and frequency-domain analysis. The models presented by him were based on simulations and measurements and contain the parameters that were necessary to maintain practical accuracy. Based upon simulations using parameter values commonly found in PLC systems, the system elements that dominate the low order frequency response of the PLC systems were the drain coil, the equivalent series capacitance in the line tuner, and the equivalent load impedance. Of course, the PLC system configuration also significantly affects the low order frequency response. There simulations revealed that PLC systems most susceptible to resonance problems were single- and dual-frequency configurations that have the combination of a high-frequency tuning capacitor and a large value (≥ 100 mH) drain coil. If the voltage was at the resonant frequency of a PLC system with a 10 dB gain at the drain coil, the voltage impressed on the PLC circuits would be 4200 V, which was well in excess of the allowable limits for PLC systems [32].

In 2005, K. Y. See et al. proposed the CM noise propagation model based on a two-current-probe measurement approach, for a three-wire power-line cable and represented an equivalent two-wire CM transmission line. The equivalent CM noise propagation model allows them to predict the CM noise current on the power line with reasonable accuracy. As the distributed per-unit length CM propagation parameters were derived through measurement, the model established included the losses of the power line as well as factors related to the power-line layout and its surrounding materials. With the knowledge of CM noise propagation model of the power line, the level of the CM current on the power line for different cable lengths and different loading conditions were estimated. The accuracy and reliability of the CM noise propagation path model were verified by comparing the calculated CM current values, which were derived from the model, with the measured CM current values. The power-line cable was driven by a known CM source and terminated with a known CM load. The Agilent 4395A Network Analyzer was employed for the measurement of the S-parameters [33].

In 2005, D. Anastasiadou and T. Antonakopoulos*,* presented an analytical calculation method, which was then used to determine the multipath components of any point-to-point channel in the indoor power-line environment. The method calculated all transmission characteristics of the network. The proposed method was applied to an example network to demonstrate its usefulness in explaining the network's time-dependent behavior and in estimating channel parameters, such as sub channel bandwidth, multipath delay spread, fading conditions etc. They presented an algorithm that performed analytical calculation of the multipath effect between any pair of communicating devices on the indoor power-line network by tracing it back to its physical characteristics, such as cable loss, reflection, and transmission coefficients. Analytical calculation of the multipath components in the indoor power grid was feasible due to its loop-free topology and its bounded complexity, thus making it possible to predict the response of any point-to-point channel, based on information about the network's physical structure, topology, and termination loading. Modeling the power-line channel as a multipath environment was needed in order to determine the transmission paths that contribute to its time- and frequency-variable behavior and to determine the parameters that define the medium's communications properties, such as the root mean square (RMS) delay spread, which indirectly determines the achievable data transmission rate. Using the calculated values of every network reflection and transmission coefficient, they proceeded with the estimation of the factors that comprise each of the multipath components received on a certain point-to-point channel. They focus on describing the effect of signal distortion due to propagation in the network. The power-line channel was characterized as a multipath fading environment with time- and frequency-varying behavior. They found that time variations in its termination loading, namely, loads (e.g., electrical appliances) connected to or disconnected from the network, or even altering their impedance during normal operation, caused its impulse response to vary. The channel, however, appeared to be changing rather slowly compared to the symbol duration in high-speed data communications [34].

In 2006, Z. Mingyue introduced topology of the typical low voltage supply grid in China, and discussed the measurement methods in detail. According to the nature of distribution networks configuration, office blocks and residential buildings were tested respectively, and the methods of channel measurements were also introduced in detail. The spectrum analyzer was located after the kWh meter and the signal generator was located in the cabinet of the building. The measurements showed that the main reason influencing the reliable communication of high-speed data on power lines was the attenuation characteristics of the high-frequency signal, which can be seen more obviously in the branches of power lines. Also for the multi-layer buildings, it was almost impossible to use the frequency range from 2MHz to 20MHz to realize the reliable communication from distribution transformers to each user, which must be solved with the aid of means, such as the repeater. For high speed communication low frequency range offers less attenuation while high frequency communication was less affected by the noise. They concluded that the frequency range of 2MHz-10MHz was suitable for the high-speed data access system of power line [6].

In 2006, S. Khan et al. designed a microcontroller-based master and slave units with serial ports for communication with a computer and a transmission port to couple the signal to modems at both ends. The programming of the microcontrollers at either end for formatting the data bits before they were sent down the power line and the development of software for putting in place the required master and slave protocols was presented. The interfacing circuits were designed and tuned to frequency contents making the bits of data. The frequency performance of these coupling circuits was presented, showing the range a power line can be used for communication of such data. They faced some problem such as unpredictability of connected loads, Frequency and time dependence of impedance, attenuation and transmission characteristics; impulse and background noise and their wide variability; limited bandwidth; harmonic Interference. These issues have been addressed in the form of modeling power before using it as a reliable communication medium. There work mainly designed for the purpose of controlling electric appliances in premises such flood light control of golf courses or the control of high power lights on highways. The sending master and receiving end slaves modules were designed, properly coupling circuits were developed, and the software both fro the master and slave was written using C programming language with the help of a microchip debugger. The system was designed to work as expected and has been tested to be showing good response in a noise free environment. The device identity codes sent down the line were properly received and identified by their respective slaves and devices. Also, the slaves act to result into appropriate action on the devices connected to the slaves concerned. However, the circuit shows picking up noise in environment with loads such as exhaust fans, air conditioners and flood lamps [1].

In 2008, H. Li et al. presented a channel model of the indoor power line for broadband power line communication (BPLC).Considering transmission theory, the two-port network model of power line has been established in this paper. And according to this model, characteristics of power line channel under the different network configuration and terminate loads have been analyzed. The model has been verified with practical measurements on actual power network. It was demonstrated that the model based on two-port network theory can accurately reflect the situation of power line channel. And the result shows that the characteristic of channel was variation with frequency and network topology. The model takes into consideration of cable type and the power line network structure. Base on the simulation result, the property of the power line channel was found that the channel was attenuation with the frequency and the number of branches. The more branches were connected to the main propagation path; the much attenuation will be produced. And the effects of the load impendence were also found that the channel can be influenced by impendence mismatch deeply [35].

In 2008, J. Anatory and N. Theethayi investigated whether a finitely conducting ground return could be used for BPLC and to investigate its performance over the conventional methods where one of the adjacent power-line conductors was used as signal return. They show that the use of ground return for the BPLC system was effective or better only when the ground conductivity was high (> 50 mS/m). When ground conditions were poorer, attenuations increase with frequency, making them unsuitable for BPLC. The analysis presented by them was based on transmission-line solutions both under lossless (without ground return) and lossy (with ground return) conditions and were applied to typical low-voltage and medium-voltage channels. Comparisons were also made based on the power spectral densities and channel capacities. In MV lines, as ground conductivity tends to decrease, attenuations tends to increase with frequencies, while for adjacent conductor return, the attenuation was more or less unaffected compared to ground return. For ground with lower permittivity as the frequencies increase, the attenuation increases. For LV lines, it was observed that as ground conductivity tends to decrease, attenuations tend to increase with frequencies but less severe compared to the MV line. As the frequency increases, the relative permittivity does not influence the channel in the frequency bands of 0–30 MHz compared to the MV line. For MV and LV lines with branches, the number of peaks and notches for a given frequency window increases with the line length with either the adjacent conductor return or ground return. When the ground conductivity was lower, the channel tends to attenuate more with frequency, however, at high-frequency attenuations, constant values were attained. For the MV channel, the channel capacity decreases with decreasing ground conductivity [36].

In 2009, A. Agarwal reviewed the source of attenuation, noise and distortions encountered when communicating over power line. Various technologies which have been used to address these challenges, such as multicarrier modulation, spread spectrum techniques were then examined. Modeling and Simulation Tools were discussed. She presented the LV power line as a communication medium for broadband transmission. The channel characteristics and communication techniques were discussed. The power line communication model has also been discussed briefly [37].

CHAPTER 4

PROBLEM DESCRIPTION AND PROPOSED SOLUTION

4.1 Problem

In a household there are more than one electric socket boards. This thesis assumes a household with more than two rooms each having power plugs on one of their walls. The basic need is to share various resources among some of the household equipments placed in separate rooms. One example of such a problem is depicted in Figure 4.1. The figure depicts three rooms with power plugs on their walls. The distance between room1 and room2 is labelled as L1 similarly L2 is the distance between room2 and room3. One solution to this is to set up Local Area Network (LAN) but this would result in additional installation cost. To take advantage of the existing infrastructure, power line carrier would be a resourceful approach towards this communication requirement.

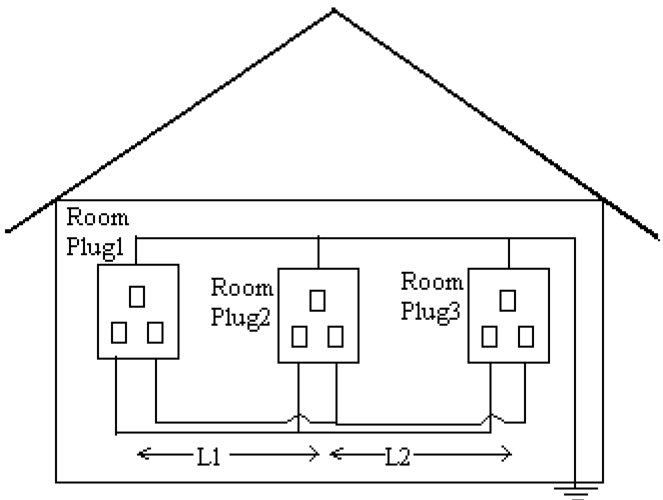


Figure 4.1: Schematic of a typical Household with three Rooms.

Now, the links between each room within particular household might be different channels with different characteristics and qualities. The quality is estimated from how good the communication is on a channel. The quality is mainly a parameter of the attenuation of the electrical signal at different frequencies. This thesis simulates a transfer function model of main PLCC channel connecting two power points within a household. Although research has shown that the attenuation is a parameter of the physical length of the channel yet effects of diameter and separation between the power cables must not be neglected. Length, diameter and separation are effortlessly known system parameters furthermore the knowledge of system model would lead to efficient use of offered resources. Keeping under consideration that bandwidth is a valuable and limited resource, the dependability of bandwidth upon various system features i.e. diameter and length of power cable and the separation between power conductors is also determined.

4.2 Proposed Solution

This section gives an explanation to the steps towards the design of proposed PLCC channel model and furthermore the model analysis for its frequency response and bandwidth dependability on physical parameters namely cables diameter, cable length and the separation between the power cables. As already been discussed the model is derived from transmission line theory and two port model analysis of power lines. Following are the step by step description of the proposed solution to the problem. A very important thing to be noted here is that the model describes the behaviour of in building PLCC channel thus all the analysis will be carried out by considering lumped parameters.

4.2.1 Transmission Line Analysis of Power Line

The Electromagnetic Theory states that to achieve efficient point-to-point transmission of power and information, the source energy must be guided. When power lines are used to communicate high frequency information signals, they can be considered as transmission lines, which guide the Transverse Electromagnetic (TEM) waves along them. The typical indoor power line uses single-phase wire which is comprised of two conductors with Polyvinyl Chloride (PVC) insulation. Cross-section of these conductors is usually 2.5mm^2 or 4mm^2 [36]. When the high frequency signals transmission in power line, it can be approximated as a close form of the "two-wire transmission line". The cables are made up of stranded copper conductors with PVC insulation. The three cables (live, neutral, and earth) are usually laid inside metal conduit as shown in Figure 4.2 that are embedded inside the concrete wall. Typically, the live and neutral cables are used as the PLC transmission channel, which can be approximated as a close form of the "two-wire transmission line".

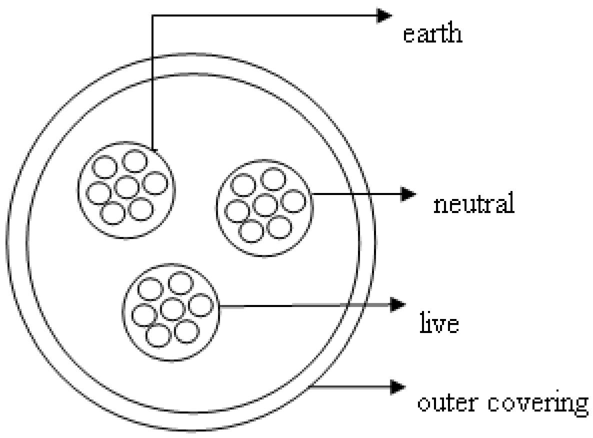


Figure 4.2: Cross-sectional view of the House Service Power Line.

According to [31], the two-wire transmission line must be a pair of parallel conducting wires separated by a uniform distance. In the actual installation, the power cables are simply pulled through the conduit and the separation between them is not uniform at all. However, the conduit normally has small cross-sectional area and this limits the variation of the separation between the cables. Hence, the assumption of uniform separation is reasonable in this case.

4.2.1.1 Primary Line Parameters

Every electrical network consists of resistance, capacitance, inductance and conductance as its primary parameters. When an ac current flows in a conductor, the self-inductance within the conductor causes more current to flow near to the outer surface of the wire instead of toward the centre. This phenomenon is called the skin effect [27]. This effect causes an increase in the resistance of the cable and it worsens as the current frequency increases. Although the current flow is still distributed throughout the cross section of the cable, when calculating the resistance, it is normal to assume that all the current flows within the "skin depth" of the cable. The skin depth 'δ' is a function of frequency 'f' and can be calculated as:

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}$$

Where 'σ' is the conductivity of conductor and 'μ' is permeability in free space, which has a constant value of:

$$\mu = 12.566370614 * 10^{-7}$$

According to transmission line theory, the four primary line parameters are resistance 'R', capacitance 'C', inductance 'L' and conductance 'G' and are given by:

$$R = \frac{2}{a}\sqrt{\mu f/\pi\sigma}$$

$$C = \frac{\pi \in}{cosh^{-1}(\frac{d}{a})}$$

$$L = \frac{\mu}{\in} cosh^{-1}\left(\frac{d}{a}\right) + \frac{R}{2\pi f}$$

$$G = 2\pi f C \tan\delta$$

Where 'a' is the diameter and 'ε' is permittivity in free space.

The permittivity of free space (sometimes called the vacuum permittivity) is a constant of nature that specifies how strong the electric force between electric charges is in vacuum, or put another way it tells us how strongly the electric field reacts to the presence of charges in empty space. This quantity is normally represented with the symbol ε_0 (read 'epsilon zero' or 'epsilon naught').

In SI units, the vacuum permittivity is defined to have an exact value of:

$$\varepsilon = 1/(\mu c^2)$$

Where 'μ' is the magnetic permeability of free space and 'c' stands for the speed of light in vacuum. This has the approximate numerical value:

$$\varepsilon = (8.854\ 187\ 817) * 10^{-12}\ F/m$$

In more familiar units, F/m = C^2/ (N m^2).

4.2.1.2 Model Parameters

Based on transmission line theory, the propagation constant 'γ' and characteristic impedance 'z_0' can be written as:

$$\gamma = \alpha + \beta = \sqrt{(R + j\omega L)(G + j\omega C)}$$

$$z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

Where the parameter 'ω' is the angular frequency, real part 'α' and the imaginary part 'β' of the propagation constant are the attenuation constant in Np/m and phase constant in rad/m respectively. Note that both 'γ' and 'z_0' are characteristic properties of the transmission line. They depend on 'R', 'L', 'G', 'C' and 'ω' but not the length of the line.

4.2.2 PLCC Channel Model

The transfer function of indoor power line without any distribution branch can be written as:

$$|H(l)| = \left|e^{-\gamma l}\right| = e^{-\alpha l}$$

Where '*l*' is the length of Indoor power line and 'e' is well familiar exponential function.

However, that is only demonstrating the situation of a single loop without branches. Due to existing branches, impendence mismatch which can produce some multi-path reflections, the actual situation is far more complicated.

According to transmission theory, a uniform transmission line can be modelled as a two-port network. Considering a typical indoor power line as a uniform transmission line, the relationship between input voltage/current and output voltage/current can be demonstrated as a two-port network [36]. The relationship between current and voltage at these two ports can be written as:

$$\begin{pmatrix} U_1 \\ I_1 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} U_2 \\ I_2 \end{pmatrix} = T \begin{pmatrix} U_2 \\ I_2 \end{pmatrix}$$

Where 'U_1' and 'I_1' are input voltage and current, 'U_2' and 'I_2' are output voltage and current respectively and 'T' is transfer matrix. The parameters in transfer matrix 'T' reflect the relationship between two ports. Therefore, the structure of power network will influence the detail of matrix. The main propagation path purely consists of transmission line. So according to transmission line theory, the transfer matrix of main propagation can be written as:

$$T = \begin{bmatrix} \cosh(\gamma l) & z_0 \sin h(\gamma l) \\ \frac{1}{z_0} \sin h(\gamma l) & \cosh(\gamma l) \end{bmatrix}$$

Parameter 'γ' is propagation constant, '*l*' is the cable length and 'z_0' is impendence characteristic of power cable.

The transfer function of PLCC channel is given by the following expression:

$$H(f) = \frac{U_2}{U_1} = \frac{Z_L}{AZ_L + B}$$

The parameter 'A' and 'B' are two port model parameters as given in transfer matrix 'T'.

4.2.3 Transfer Function Simulation

The MATLAB Software is used to simulate the modelled transfer function. The steps to simulate frequency response are as follows:

Algorithm 4.1

Step 1: Initialize 'ε' the permittivity in free space, 'σ' the conductivity of conductor, 'μ' the permeability in free space and physical parameters as 'a' the diameter, 'd' the separation between the cables and '*l*' the cable length.

Step 2: Select the frequency range and split it into an array of discrete frequencies. The simulation will have more resolution for more number of array elements.

Step 3: Calculate the values of frequency independent model parameters 'R' the resistance and 'C' the capacitance.

Step 4: By using loops calculate all frequency dependent model parameters 'L' the inductance, 'G' the conductance, 'γ' the propagation constant 'z_0' the impendence characteristic. The skin depth 'δ' is also calculated because it is frequency dependent. For loop is used to calculate the above values. Since all these parameters vary according to frequency hence these will have as equal number of elements as in array of frequencies. These parameters also correspond to arrays of same length as frequency.

Step 5: Similarly calculate 'A' and 'B' parameters and 'H' the transfer function. These are also frequency dependent and represented by arrays.

Step 6: Calculate bandwidth of the modelled channel.

Step 7: Plot transfer function array elements for corresponding frequency array elements.

4.2.4 Bandwidth analysis

To simulate the effects of physical parameters on bandwidth some modifications to the above simulation scheme are made. These modifications include selecting range of physical parameter to be considered, one at a time and calculation of bandwidth for the discrete range of that particular parameter.

To see the effect of cable length on bandwidth the succeeding steps were followed:

Algorithm 4.2

Step 1: Initialize 'ε' the permittivity in free space, 'σ' the conductivity of conductor, 'μ' the permeability in free space and fixed physical parameters as 'a' the diameter and'd' the separation between the cables.

Step 2: Select the range for the cable length and split it into an array of discrete lengths. The simulation will have more resolution for more number of array elements.

Step 3: Repeat steps 2 to 4 in transfer function simulation.

Step 4: By using nested loops calculate both frequency and length dependent entities. Increment the outer loop for the length array and the inner loop for the elements of frequency array. This gives a transfer function array for each element of length array. Calculate bandwidth for every element of length array and make an array of bandwidth.

Step 5: Plot bandwidth array elements for corresponding length array elements.

The simulation of bandwidth for diameter has some more modifications in the above algorithm. The modifications made are due to the fact that primary line and model parameters are dependent upon diameter of the power cable. To see the effect of cable diameter on bandwidth the subsequent steps were followed:

Algorithm 4.3

Step 1: Initialize 'ε' the permittivity in free space, 'σ' the conductivity of conductor, 'μ' the permeability in free space and physical parameters as'd' the separation between the cables and '*l*' the cable length.

Step 2: Select the frequency and the diameter ranges and split them into arrays of discrete frequencies and diameters respectively. The simulation will have more resolution for more number of array elements.

Step 3: Use nested loops to calculate all model parameters. Increment the outer loop for diameter and then repeat steps 2 to 6 of transfer function simulation within this loop that calculates arrays of model parameter, transfer function furthermore gives bandwidth values for corresponding frequency values.

Step 4: Plot bandwidth array elements for corresponding diameter array elements.

The simulation method of bandwidth for separation between the cables is quite similar to the above simulation scheme. The steps are given below:

Algorithm 4.4

Step 1: Initialize 'ε' the permittivity in free space, 'σ' the conductivity of conductor, 'μ' the permeability in free space and physical parameters as 'a' the diameter and '*l*' the cable length.

Step 2: Select the frequency and the cable separation ranges and split them into arrays of discrete frequencies and cable separations respectively.

Step 3: Use nested loops to calculate all model parameters. Increment the outer loop for cable separation and then repeat steps 2 to 6 of transfer function simulation within this loop that calculates arrays of model parameter, transfer function also gives bandwidth values for corresponding frequency values.

Step 4: Plot bandwidth array elements for corresponding cable separation array elements.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Transfer Function Modelling Results

The transfer function is derived from two port model of the power line carrier communication channel. This model takes advantage of transmission line theory of power lines. The model makes use of very basic transmission system parameters i.e. length, diameter and separation for the cables forming channel. These physical parameters are used to determine channel characteristics such as impedance and propagation constant. It is well known that the channel model is greatly dependent upon channel characteristics, which relies on channel's physical design. In order to know the effect of physical parameters like cable length 'l', cable diameter 'a' and separation between power cables 'd', we have simulated the gain v/s frequency response and there from we could determine the bandwidth available for a given set of parameters. Using nested loops we could plot the variation in BW as an effect of these physical parameters, taking one parameter at a time. The results of these simulations are presented in the subsequent sections. All dimensions are in SI units.

5.1.1 Frequency response of the modelled channel

To obtain the frequency response of the modelled channel we set all model parameters to certain values and simulated the channel gain for various frequencies. Figure 5.1 shows a plot between gain and frequency of the modelled channel keeping system parameters to particular values i.e. cable diameter a=1*(10^-3) m, separation d=5*(10^-3) m and cable length l=80 m. Results confirm that the channel transfer function follows a decaying trend with regard to increasing frequency. It is clear from the plot that gain decreases rapidly with an increase in frequency i.e. attenuation is much higher for high frequencies. The bandwidth was found to be 212 M Hz for this set of physical parameters.

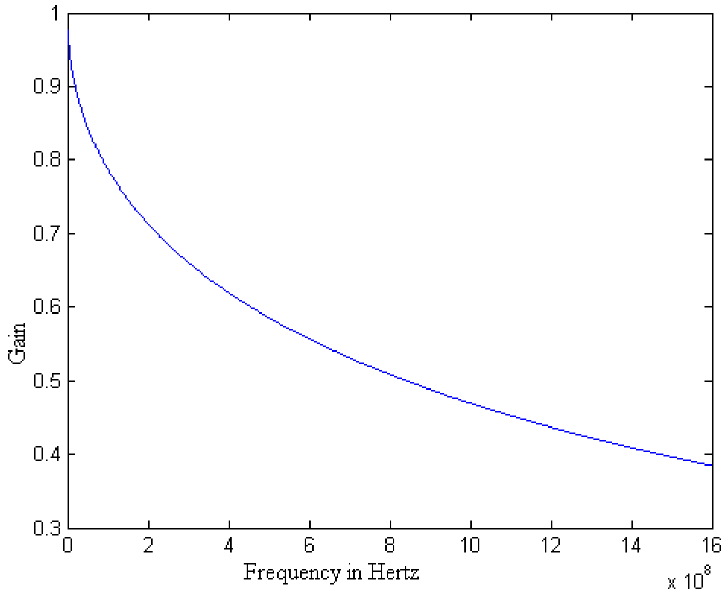
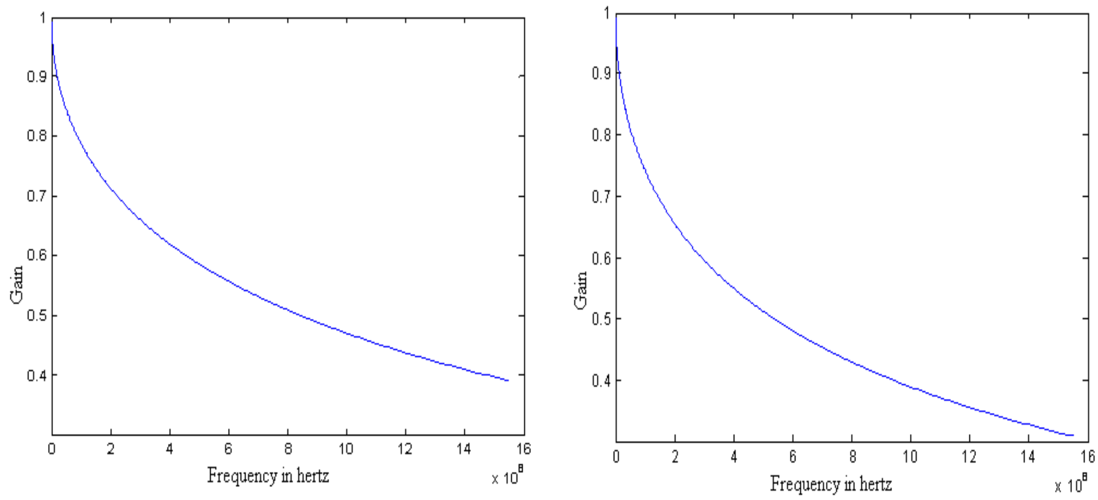


Figure 5.1: Gain v/s Frequency

5.1.2 Effect of Cable Length

To see the effect of cable length on gain of the modelled power line channel we took the same set of frequencies, diameter a=1*(10^-3) m and separation between conductors d=5*(10^-3) m. We then simulated the variations in channel bandwidth in MATLAB using nested loops. In this simulation the cable length was increased by 20 meters i.e. from l=80 m to l=100 m. The results are shown in Figure 5.2 that deduces the attenuation increases with increase in length.



(a) (b)

Figure 5.2: Gain v/s Frequency for Different Cable Lengths.

(a) At l=80 m, (b) At l=100 m.

Another observation is that the bandwidth lowers as the cable length is raised. The bandwidth has now decreased from 212 M Hz to 136 M Hz. To clarify the effects of cable length on bandwidth the same set of parameters was utilized additionally the length was varied from 50 m to 500 m. The effect of cable length upon bandwidth is plotted in Figure 5.3. The figure plots channel bandwidth in accordance with increasing length. It clears that the bandwidth decays with increasing cable length.

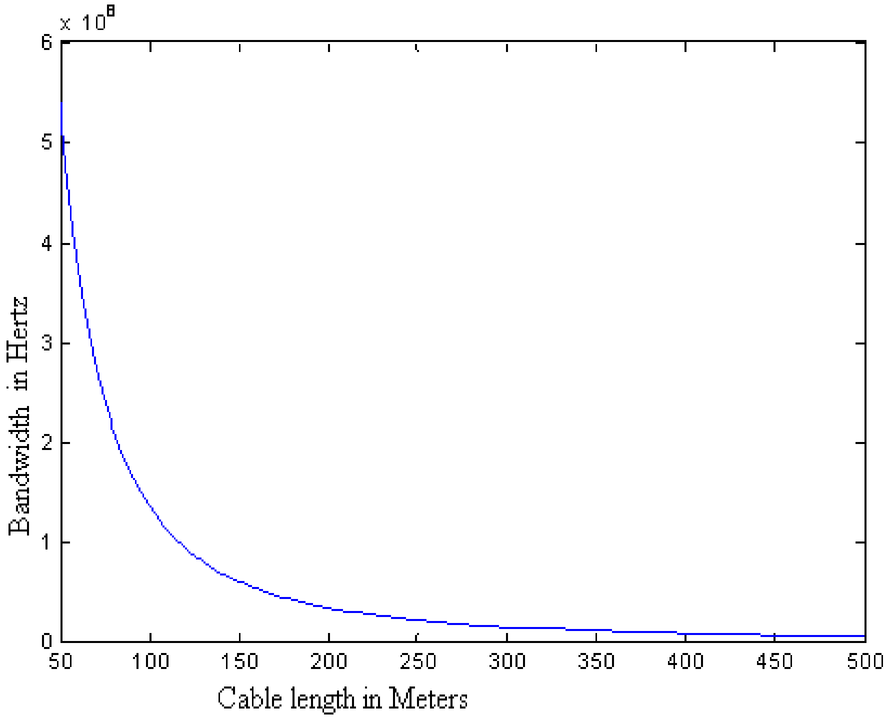
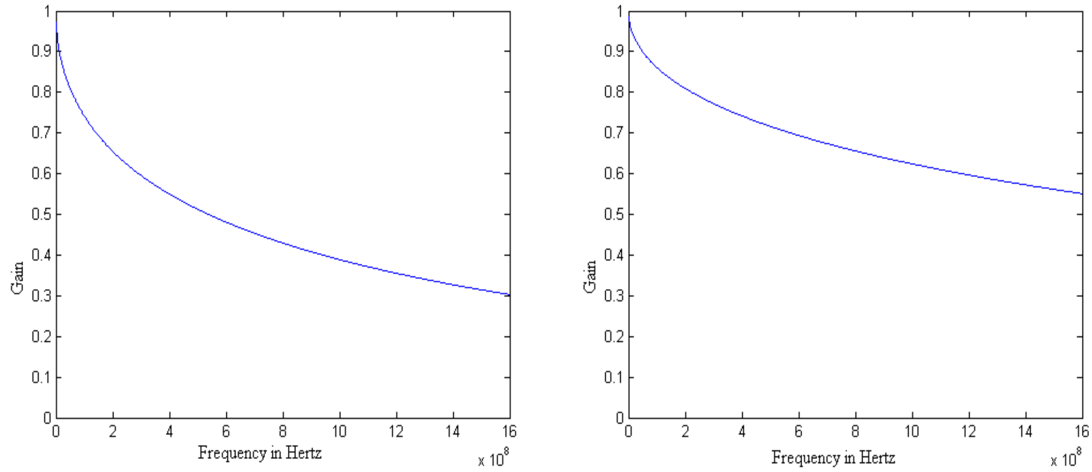


Figure 5.3: Bandwidth v/s Cable Length.

5.1.3 Effect of Separation between live and neutral power cables

In order to see the consequence of Separation between the power cables on gain of the modelled power line communication channel, we took the same set of frequencies, diameter a=1*(10^-3) m and the cable length l=100 m as in fig.2. We then simulated the variations in channel bandwidth in MATLAB using nested loops. In this simulation separation between conductors was increased by a factor of 10 i.e. from d=5*(10^-3) m to d=50*(10^-3) m. The results are shown in figure 5.4 that figure out the attenuation decreases with increase in Separation between the power cables.



(a) (b)

Figure 5.4: Gain v/s Frequency for Different Separation Between Cables.

(a) At d=5*(10^-3) m, (b) At d=50*(10^-3) m

We observed that the bandwidth rises as the separation between live and neutral cables is increased. The bandwidth has now increased from 136 M Hz to 542 M Hz. To clarify the effects of cable separation on bandwidth the same set of parameters was utilized additionally the separation was varied up to 1 m. The effect of cable separation upon bandwidth is plotted in Figure 5.5.

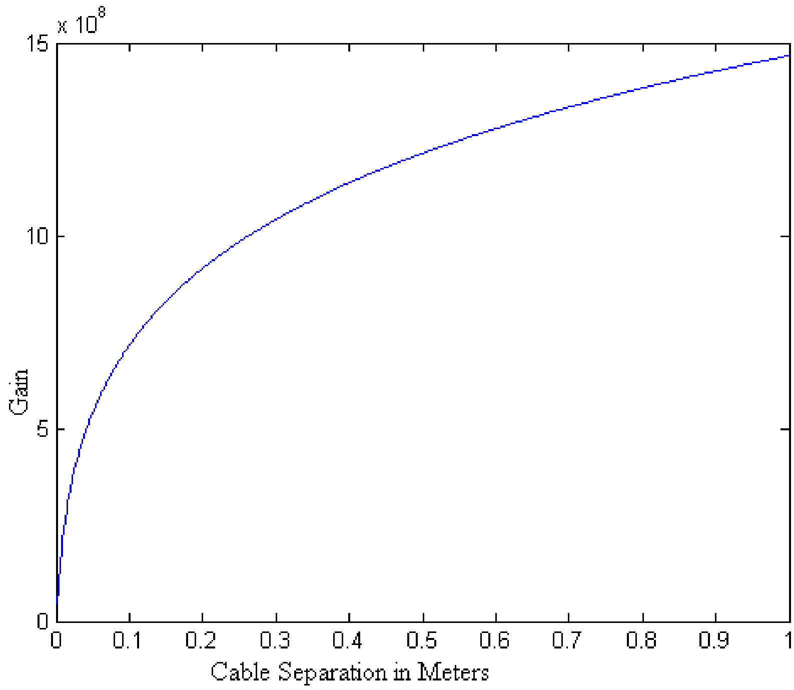


Figure 5.5: Bandwidth v/s Separation Between the Cables.

Figure 5.5 gives channel bandwidth in accordance with increasing separation. It clears that the bandwidth increases with increasing cable separation.

5.1.4 Effect of Cable Diameter

Moving towards simulating the effects of final parameter i.e. cable diameter on gain of the modelled power line channel, we followed the similar procedure as in above cases. We took the same set of frequencies, cable length l=100 m and separation between conductors d=5*(10^-3) m. While we changed cable diameter from a=1*(10^-3) m to a= 2*(10^-3) m. We then simulated the variations in channel bandwidth in MATLAB using nested loops. The results shown in Figure 5.6(a) and Figure 5.6(b) seems to show that attenuation decreases with increase in cable diameter. The bandwidth here has increased from 136 M Hz to 242 M Hz.

But the most interesting result came when we further increased the cable diameter to a= 4.5*(10^-3) m by keeping all other physical parameters unchanged. This is given in Figure 5.6(c) where attenuation has increased for these set of physical parameters as well as the bandwidth has dropped to 114 M Hz.

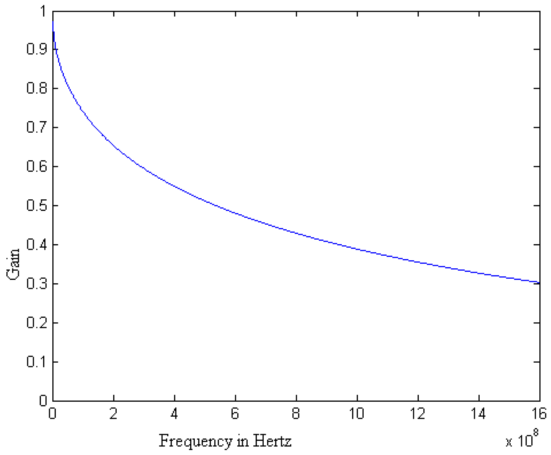


Figure 5.6 (a): Gain v/s Frequency for a=1*(10^-3) m.

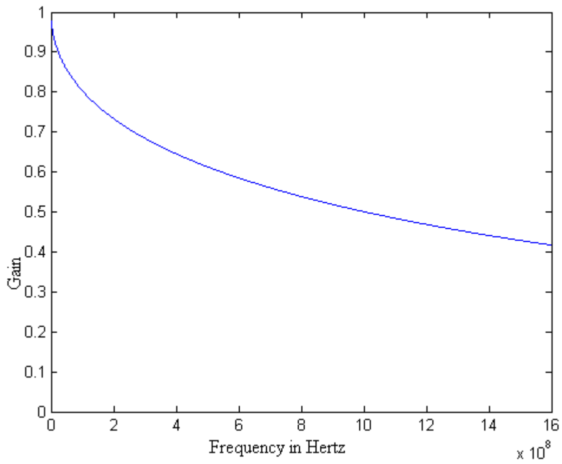


Figure 5.6 (b): Gain v/s Frequency for a= 2*(10^-3) m.

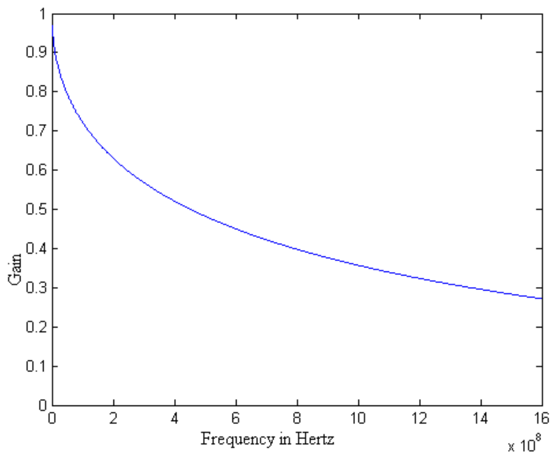


Figure 5.6 (c): Gain v/s Frequency for a= 4.5*(10^-3) m.

Thus it became necessary to clarify the effects of cable diameter on bandwidth. We again utilized the same set of parameters i.e. cable length l=100 m and separation between conductors d=5*(10^-3) m in addition the cable diameter was varied beyond 4.5*(10^-3) m. The effect of cable diameter upon bandwidth is plotted in fig. 5.7. The figure gives channel bandwidth in accordance with increasing cable diameter.

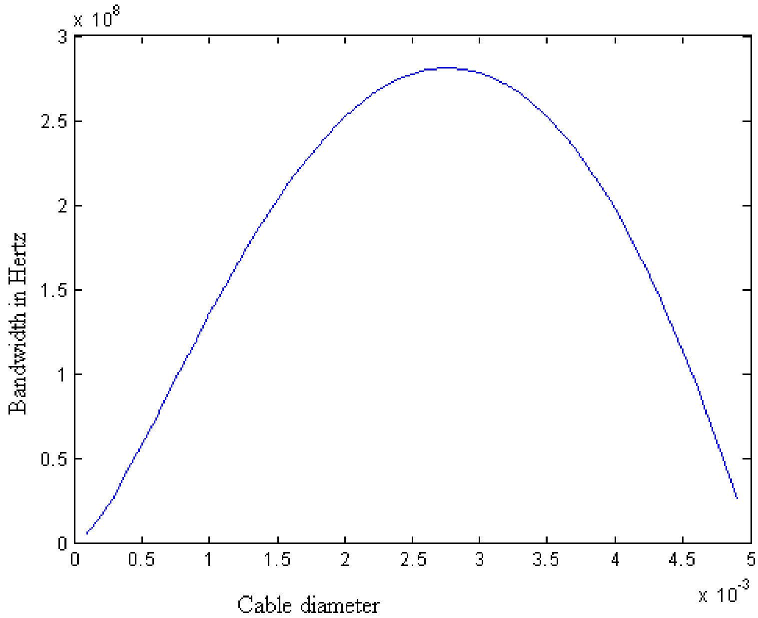
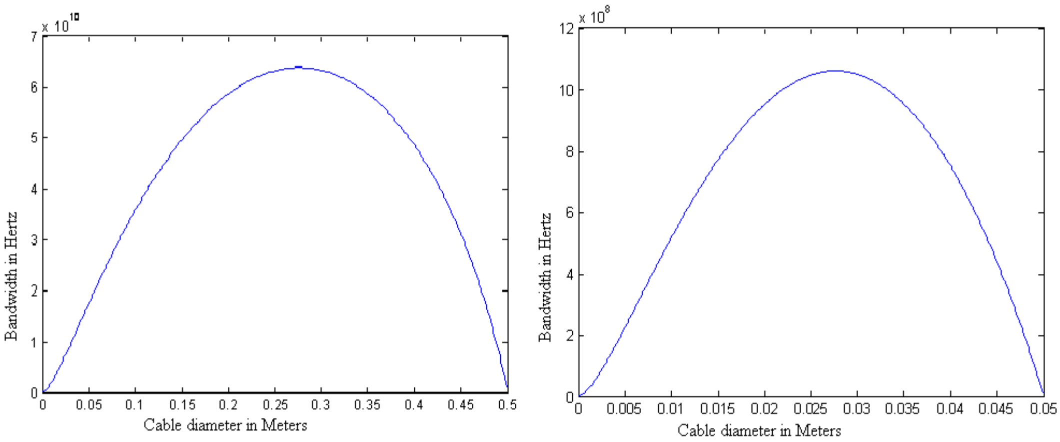


Figure 5.7: Bandwidth v/s Cable Diameter.

The simulation results for bandwidth against cable diameter show that an increase in the cable diameter makes the bandwidth to reach its highest value at a definite diameter and then the channel bandwidth drops off. In other words there exists a diameter before which the bandwidth increases and after this diameter the bandwidth decreases. The bandwidth is largest at this diameter therefore for a particular set of other physical parameters this result is of great importance in determining the maximum attainable bandwidth using this diameter.

For a typical household, the diameter and separation are not easy to modify if once the wiring is done. Thus we tried to simulate the above result with a different separation between the electrical wires. This time we took d= 50*(10^-3) m, l= 500 m in one simulation and d= 500*(10^-3), l= 500 in other simulation to compare the figures and realize the effect of cable separation on maximum bandwidth diameter.



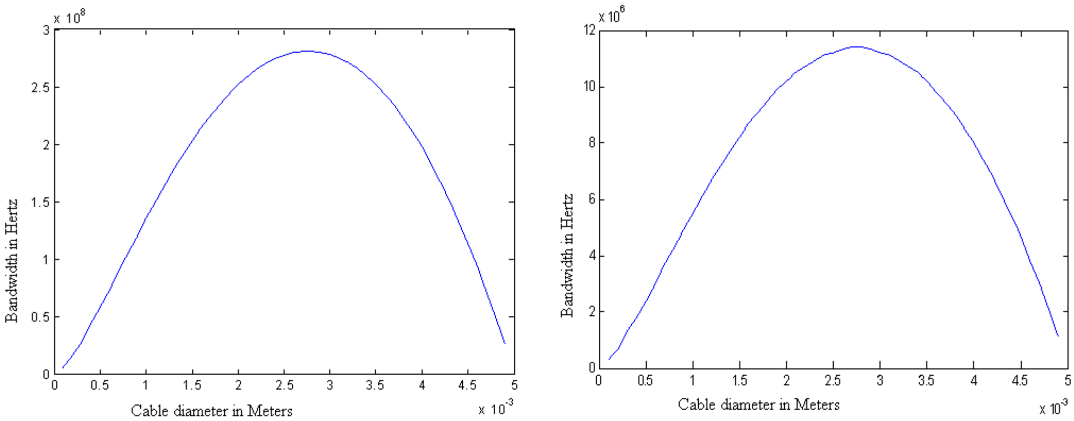
(a) (b)

Figure 5.8: Bandwidth v/s Cable Diameter for Different Cable Separations.

(a) At d= 500*(10^-3) m , (b) At d= 50*(10^-3) m

The simulated result shown in Figure 5.8 reveals that if the separation between the cables is modified to n times the present separation then the maximum bandwidth is achieved at a diameter that is also n times the present diameter.

In a household particularly the one we have considered in our problem, we would be communicating form one room to another and eventually we might be communicating between another pair of rooms. Hence the cable length keeps on changing as a result the network structure must be designed in such a way that the data rate does not change with changing cable length.



(a) (b)

Figure 5.9: Bandwidth v/s Cable Diameter for Different Cable Lengths.

(a)At l= 100 m, (b) At l= 500m.

The channel model results show that the maximum bandwidth diameter has no effect on its value if the cable length is changed. This is illustrated in Figure 5.9 in which the separation is kept same as d=5*(10^-3) m, but cable length is kept l= 100 m and l= 500 m in two simulations.

CHAPTER 6
CONCLUSION AND FUTURE SCOPE

6.1 Conclusion

The low voltage single phase power line carrier communication channel is modeled as two-wired transmission lines and the two intrinsic line parameters namely characteristic impedance and propagation constant are derived. Making use of the line parameters, the transfer function for PLCC channel is determined based on two-port network theory. The model takes into consideration of the physical dimensions of power cable and assumes a particular network structure. Base on the simulation result, the property of the power line channel is found that the channel attenuation increases with the increase in frequency.

The model is readily available to represent the channel of indoor power line. It can predict the system performance and can be used for hardware implementation of PLCC compatible modems, printers etc. Based on the understanding gained through the characterization and modeling of power lines, proper signalling and detection methods might be determined for the design of broadband PLCC systems in future. In addition, by modeling the power line as the transmission line, not only the transfer function, but also the input impedance of the power network can be obtained. The input impedance plays an important role in designing the transceiver matching circuits and determining the transducer gain and signal power.

Simulation results show that the bandwidth varies if a change in physical parameters like length, diameter and separation between power carrying cables is carried out. Bandwidth increases with increase in separation between live and neutral cables but an increase in cable length causes reduction channel bandwidth. While an increase in the cable diameter makes the bandwidth to reach its maximum value at a certain diameter and then drop off. This maximum bandwidth diameter has no effect on its value if the cable length is changed but if the separation between the cables is modified to n times the present separation then the maximum bandwidth is achieved at a diameter that is also n times the present diameter.

These results are of great importance in determining the achievable maximum bandwidth within a household. As the date rate is dependable upon the bandwidth, the maximum reliable data rate can also be estimated using this model.

6.2 Future Scope of Research

This thesis work considers power line channel of a household. The research can be extended to larger in building range including flats and office complexes. Also the problem discussed in the thesis has assumed that if the information is to be communicated between two sockets then the remaining sockets on the channel does not supply any other equipment. Practically in real application of the modelled PLCC channel, there are home appliances regularly getting power supply through some of the sockets and rest of the sockets on the main PLC communication channel might also be engaged by some appliance for short duration of time. As it has been already discussed that power line channel characteristics show variation in effect to changing impedance of connected loads thus the efforts may also be carried out to model the power line channel along with the parallel connected loads forming branches in main channel. Either in an experimental setup or by measuring the channel parameters of a typical household, the channel model has a legal scope towards its verification. Power line communication is noisy and a separate model for the noise would enhance advantage of PLCC channel model. Developing a noise model would lead to simulation of the background noise on the PLC channel offline on a computer. By producing such noise on a computer, the effects of noise through simulation of communication systems and the evaluation of the performance of such systems in the presence of noise can be predicted.

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