Modelling and Characterization of Power Line Communication Channel

A Thesis submitted in partial fulfilment of the Requirements for the degree of

Master of Technology

In

Electronics and Communication Engineering

Specialization: Communication and Networks

By

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National Institute of Technology, Rourkela,

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Under Guidance of

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CERTIFICATE

This is to certify that the thesis entitled, "***Modelling and Characterization of Power Line Communication Channel***" submitted by Kaustubh Kale (213EC5241) in partial fulfilment of the requirements for the award of Master of Technology degree in Electronics and Communication Engineering with specialization in "Communication and Networks" at National Institute of Technology, Rourkela (Deemed University) and is an authentic work by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other university/institute for the award of any Degree or Diploma.

Date:

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Dedicated to my Loving Parents

and respected teachers

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ABSTRACT

Massive advances in the field of renewable energy sources have created a need for an infrastructure incorporating both renewable and non-renewable energy resources. Also the pressing need of increasing power demand seeks an infrastructure which can fulfill the growing demands. Smart grid technology is emerging out to resolve such issues. Smart grid communicates with its entities to provide intelligence to the whole electricity delivery system. Thus the communication infrastructure is an essential part of such an emerging technology. Creation of an intelligent system for smart grid requires a reliable communication system.

Power line communication is a communication backbone of smart grid system. It is viewed as an alternative for local area network and wireless communication at home premises. It enables communication between various domains of smart grid infrastructure. It serves as a communication media at customer premises and as a last mile communication.

Recent advances in power line communication technology has created a large demand for access to network services inside premises. Power line communication has emerged as a strong candidate under such circumstances. Quality of service in power line communication relies heavily on characterization of the medium. This paper analyses the channel characteristics of power line. A transmission line model for high-frequency Power line channel is used to study the transfer characteristics of multibranch power line.

In the present thesis, power line communication channel modelling is mainly focused. The channel modelling being essential part of any communication system is analysed thoroughly and observations are drawn from the simulation results obtained. All the simulations are performed in MATLAB simulation environment.

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ACRONYMS

AMI	Automatic Metering Infrastructure
BPSK	Binary Phase Shift Keying
DER	Distributed Energy Resources
DMS	Distribution Management System
DR	Demand Response
EMS	Energy Management System
ESI	Energy Services Interface
FAN	Field Area Network
HAN	Home Area Network
IED	Intelligent Electronic Devices
IHD	In-home display
ISO	Independent Systems Operator
LMS	Load Management System
MSI	Market Services Interface
NIST	National Institute for Standards and Technology
OFDM	Orthogonal Frequency Division Multiplexing
PEV	Plug-in Electric Vehicle
PLC	Power Line Communication
QPSK	Quadrature Phase Shift Keying
RTO	Regional Transmission Operator
RTP	Real Time Pricing
SCADA	Supervisory Control and Data Acquisition
SG	Smart Grid
WAN	Wide Area Network

CHAPTER 1

INTRODUCTION

1

INTRODUCTION

1.1 Background

The current electrical infrastructure has served us more than a hundred years. But it is not suited for the growing demands of twenty first century. Today, it heavily relies on non-renewable energy sources which are on the verge of extinction. The existing grid has several drawbacks such as lack of automated analysis and lack of situational awareness. Also it cannot tackle the problems like climatic changes, equipment failure, energy storage problem, limited generation capacity. Consequently, a new grid infrastructure is needed to fulfill the growing demands for improved power quality [1].

A new concept emerged out with the idea of a two way flow of electricity and information. Smart Grid is an electricity delivery system integrated with communication and information technology for enhanced grid operation, customer services and environmental benefits. It integrates reliable, high speed and secure data communication networks to effectively manage the complex power systems.

Smart grid has emerged as a candidate solution to the energy crisis. It incorporates renewable energy resources such as wind, hydro, solar, geothermal, and tidal. These are also called green energy resources as they do not release carbon dioxide. Smart grid also supports small scale generation of energy at customer premises. Such features of smart grid reduce the burden on conventional non-renewable energy resources like petroleum, water, coal etc. Thus smart grid reduces fuel consumption and emission of greenhouse gases to a large extent [2].

1.2 Smart Grid Reference Model

National Institute for Standards and Technology (NIST), USA developed a model which divides smart grid system in seven domains. Every domain has its own significance and carries out dedicated tasks in order to establish smart grid system [3]. Smart Grid is a co-located communication infrastructure which coordinates the distributed functions across the entire power system. It consists of bulk generation, transmission, distribution and customer domains which constitute currently existing electricity delivery infrastructure. Three new domains include the operations, market and service provider which were added to provide smartness and intelligence to the system.

The discussion of seven domains follows, which is based on NIST smart grid framework. NIST has developed a reference model for every domain highlighting key components and features.

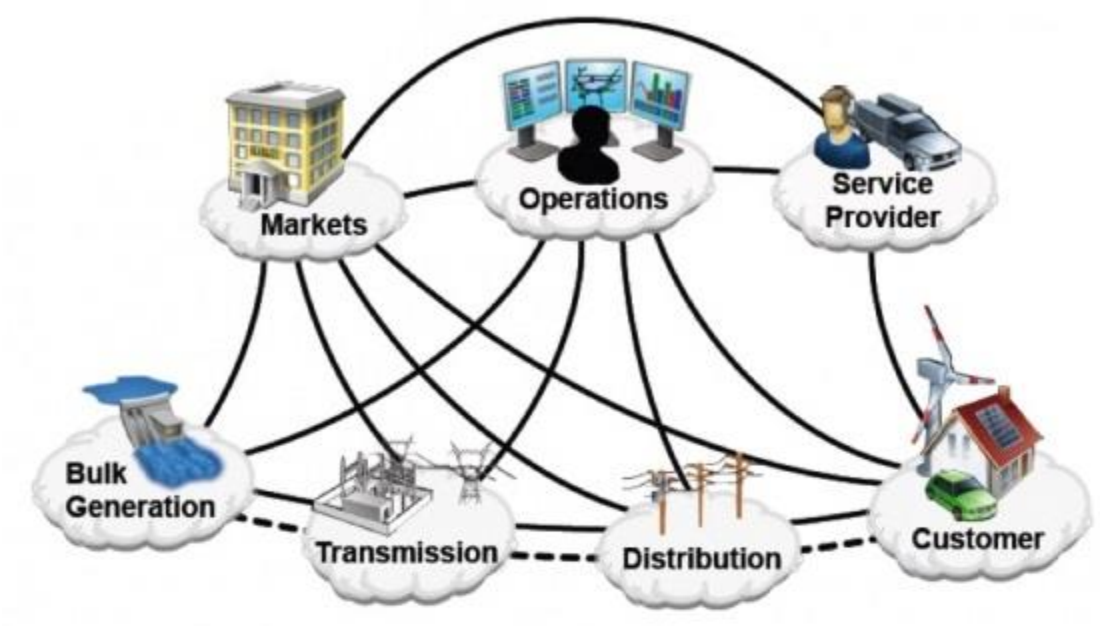


Figure 1.1: *Smart Grid Reference Model [NIST smart grid framework 1.0]*

1.2.1. Bulk Generation domain

At the bulk generation domain, the non-renewable resources like fossil fuel, gas, coal, water, nuclear fission and renewable resources like sunlight, wind, tide, hydro and biomass are used to generate electricity. Bulk generation domain and transmission domain are physically connected through number of substations [1]. This domain also communicates with Market domain over Market Services Interface (MSI) and with operations domain over Wide Area Network (WAN). The parameters like generation capacity and scarcity are communicated to these domains. These parameters are utilized to maintain balance between demand and supply. There is always a possibility of generation of surplus energy. So this domain also facilitates storage of electricity. The energy so stored can be utilized at the time of scarcity [3].

1.2.2. Transmission domain

The main function of transmission domain is to carry the electricity to distribution domain. Transmission domain consists of substations, Regional Transmission Operator (RTO), Independent Systems Operator (ISO) and transmission lines. Substations carry out most of the responsibilities of transmission domain. To achieve functions like self-healing and situational awareness, a bidirectional communication is needed between substations and control centres. Transmission domain handles this communication. It sends all the information collected from grid to operations domain and in response to that, substations in transmission domain receive commands from control centres [1].

1.2.3. Distribution domain

Distribution domain interconnects customer domain and transmission domain to all the metering points. Dispatch of energy to end users as per consumer demand and energy availability is the main responsibility of distribution domain. Distribution domain supports Distributed generation and storage [1]. The quality of electricity mainly depends upon the stability of this domain. Thus it is continuously monitored by operations domain. Control commands are exchanged with Distributed Energy Resources (DER) to maintain stability. This domain also communicates consumption and generation information with market domain.

1.2.4. Operation domain

Operations domain carries out functionality like monitoring and control, fault management, maintenance, metering etc. It communicates with transmissions domain using Energy Management System (EMS) and with distribution domain using Distribution Management System (DMS) in order to maintain efficiency. Functions of Operation domain include Network Operations, Monitoring, Control and analysis, Fault Management, Records and Assets management, Maintenance and Construction, Customer Support, Meter Reading and Control and Security Management [1].

1.2.5. Market domain

Market domain is the place for selling assets. It consists of suppliers, traders and retailers. Traders buy electricity from suppliers of bulk energy and sell it to retailers. Retailers sell it to the end users [1]. This domain maintains balance between Demand and supply. For effective balance, this domain communicates with and Customer domain. Communication between market domain and other energy supplying domains (like bulk generation domain and Distributed Energy Resources-DER) is very critical as production-consumption balance is based on this communication. DERs exist in three domains viz. transmission, distribution and customer domain.

1.2.6. Service Provider domain

This domain handles billing responsibilities. To obtain metering information, it communicates with operations domain. It also provides smart services like management of energy and home energy generation over ESI. Production of new services and products is handled by service provider domain. These new services may include value added services like account management, In-home display etc. The main concern of service provider domain is not to compromise security, stability and safety while dealing with services. So cyber security measures are needed to protect power infrastructure from external services [1].

1.2.7. Customer domain

Customer domain includes home, commercial and industrial buildings. Customer domain and distribution domain are electrically connected. This domain contributes in the process of demand response. Energy Services Interface (ESI) is used to establish two-way communication between customer domain and other domains in the system. With the help of ESI, data and control signals are exchanged between utility and smart devices at customer premises [1].

1.3. Smart Grid Communication Architecture

Creation of an intelligent system for smart grid requires a reliable communication system. This is established through a communication architecture which incorporates Wide Area Networks (WAN), Field Area Networks (FAN) and Home Area Networks (HAN). NIST has developed a smart grid communication architecture which is presented in Figure 1.2 [4].

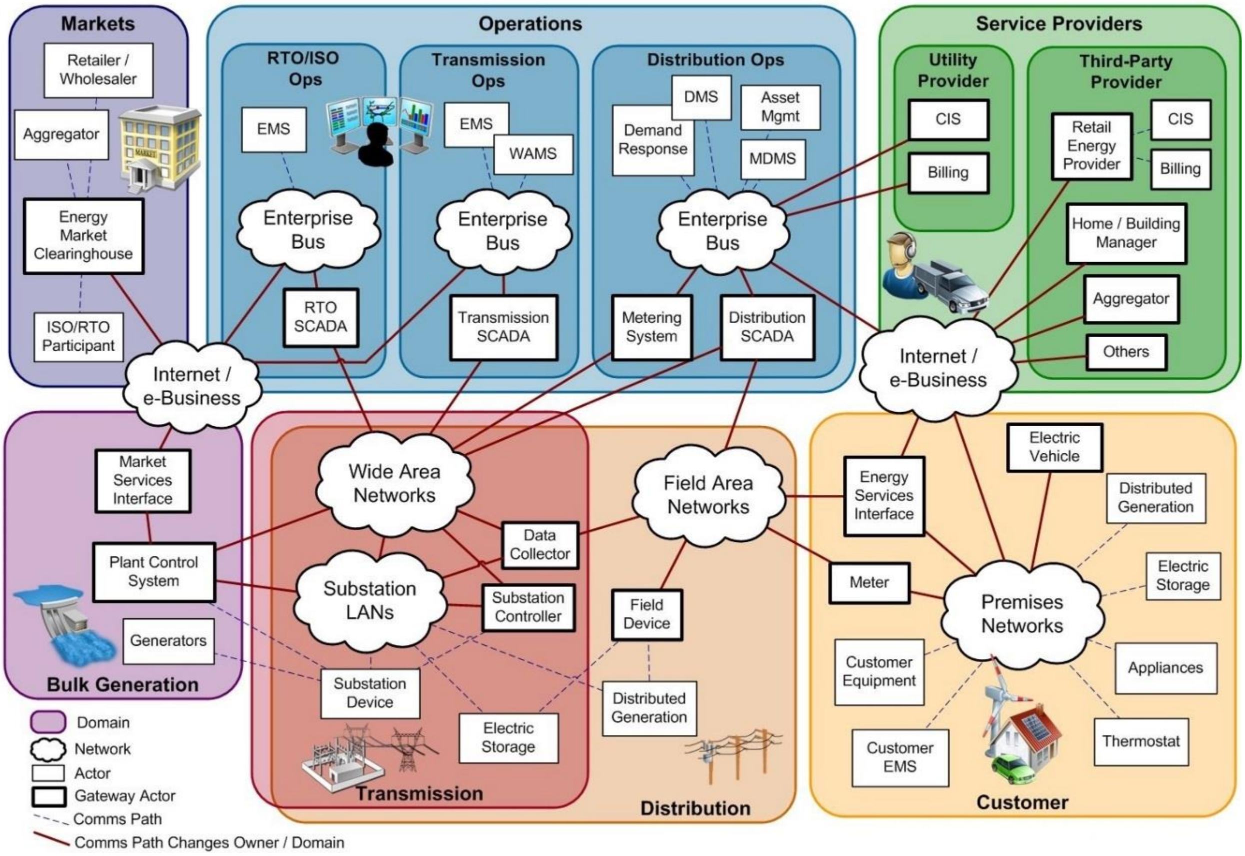


Figure 1.2: Smart Grid Communication Architecture

The architecture shows the communication technologies which are used by smart grid system to establish communication within seven domains. It has dedicated two-way communication channels and Supervisory Control and Data Acquisition (SCADA) system is used to manage these channels. Internet is also used to connect various domains through reliable interfaces. A dedicated enterprise bus is used to handle communication within operations domain [5].

1.3.1. Home Area Networks (HAN)

HAN is sometimes referred as Premises Area Network (PAN). It is the smallest subsystem in the communication hierarchy. HAN exists at customer premises and has responsibility of monitoring and control. Implementation of additional features like Demand Response (DR) management and Automatic Metering Infrastructure (AMI) is also performed by HAN [4].

HAN consists of smart meters, smart devices with sensors, In-home display (IHD). HAN connects customer equipment, appliances and DERs to smart grid infrastructure. It supports distributed generation and electricity storage at customer domain. Energy Services Interface (ESI) is a secure interface a customer premises. It provides two-way interactive communication between utility and the customer. ESI is connected to smart meters through HAN. It receives Real Time Pricing (RTP) information on AMI and sends it to utility. End user can use IHD display panel at customer premises to access pricing information from utility. HAN also helps to implement demand response process. In this process, AMI sends load control commands to smart devices using ESI. Then a load control algorithm is used to manage DR functionality [1].

1.3.2. Field Area Networks (FAN)

Field Area Networks provide means of communication for the components of Distribution domain. Following components use FAN for exchanging information with control centres [1].

1) Electrical sensors on transformers and feeders.

2) Intelligent Electronic Devices (IED) which carry the control commands from DMS and DERs.

3) Charging stations for Plug-in Electric Vehicle (PEV).

4) Smart meters at customer premises.

Field Area Networks handle field based as well as customer based applications. Field based applications are related to transmission lines, sensors etc. Such applications demand higher time sensitivity. Customer based applications like AMI, DR and Load Management System (LMS) require scalable communication infrastructure which can enable addition of new services and applications.

1.3.3. Wide Area Networks (WAN)

Wide Area Networks are the communication backbone. WANs connect highly distributed smaller area networks. Generally the control centres are located far away from substations and end users. In such cases, WANs are used to carry real-time measurement information from electric devices to control centres. WANs also carry control commands from control centres to electric devices at substations [4].

WANs are also used to establish secured communication between Intelligent Electronic Devices (IED) and control centres. IEDs collect data from substations as well as along the transmission lines. This data is basically a local SCADA information which is used for handling control and protection commands. Collection of high speed Phasor Measurement Unit (PMU) data needs higher bandwidth. WANs provide means to carry PMU data to control centres.

1.3.4. Supporting Communication Technologies

In Table I, various communication technologies those support three sub-networks (HAN, FAN and WAN) are listed [5].

Sub network	Supporting technologies
HAN	Ethernet, Power Line Communication (PLC), ZigBee, Bluetooth, Wi-Fi
FAN	PLC, Digital Subscriber Line (DSL), Mobile cellular network, Long Term Evolution (LTE), Wi-Max, IP based networks like HSPA
WAN	Wi-Max, LTE, frame relay

Table 1.1: Communication technologies for sub-networks

Power Line Communication (PLC) is used in Home Area Network for establishing communication between customer domain and other domains of smart grid system. In following chapters, Power line communication and its channel modelling is discussed in details.

1.4 Objectives

Recent advances in power line communication technology has created a large demand for access to network services inside premises. Power line communication has emerged as a strong candidate under such circumstances. Quality of service in power line communication relies heavily on characterization of the medium. The main objective of the work presented is to model a power line channel and to test the channel under various topological conditions. Such analysis is needed to perfectly estimate the channel under varying channel conditions. The objectives of the thesis include:

- Modelling of power line channel by two different modelling approaches
- Analysing the effects of physical parameters on the channel
- Designing a communication system with power line channel using OFDM BPSK/QPSK

- Evaluating system performance by bit error rate calculation

1.5 Thesis Organization

The thesis is organized in six chapters. Smart grid communication system and its communication architecture are introduced in present chapter. The objectives of thesis are discussed. The chapter concludes with the thesis outline.

Chapter 2

In this chapter, a concept of power line communication and its role in smart grid system is discussed along with its advantages. Various applications of power line communication in context of smart grid are also discussed. Two PLC channel modelling types are also mentioned in this chapter.

Chapter 3

In this chapter, first channel modelling approach based on multipath effects is discussed. PLC model so obtained is then subjected to various topological changes and results were observed.

Chapter 4

Second type of channel modelling approach is described in this chapter. This approach is based on ABCD parameters. Results were compared with first approach.

Chapter 5

Power line channel with multiple branches is analysed in this chapter by considering both ideal and practical scenario. Channel response was obtained in terms of amplitude and phase plot.

Chapter 6

PLC-OFDM system is described in this chapter. To evaluate the performance of this system, a bit error rate plot was obtained for BPSK as well as QPSK modulation based PLC-OFDM system.

Chapter 7

The thesis concludes with this chapter. Limitations and future scopes of the present thesis are also discussed in this chapter.

CHAPTER 2

PLC LITERATURE REVIEW

2

PLC LITERATURE REVIEW

2.1 Background

Since 1980s, the communication over power lines is being investigated. Since then the Power line communication (PLC) has been used for low data rate up to few kilobits per second. PLC is cost effective due to the existence of infrastructure. There is no need of installing a communication channel. So the efforts are being put to establish a communication system over power lines [6] [7].

Power line communication integrates data communication with electricity delivery system. The main objective is to utilize electricity cables as a medium to carry data. PLC is a part of smart grid infrastructure. It is a core communication system for home networking. It also establishes communication between HAN and FAN. It serves as last mile connection [8].

The channel conditions for PLC are adverse so transforming it to a high data rate medium is a challenge. Time and frequency dependent attenuation, coloured background noise, periodic and aperiodic impulsive noise and high signal reflection due to the branching severely hamper the use of power lines for high data rates. However, recent developments in PLC enable broadband transmission over power lines [9].

In order to understand the behaviour of PLC, a precise channel model is needed. There are two approaches, namely, Top-down approach and Bottom-up approach. Any of the two approaches may be implemented to model power line channel. In this chapter, power line modelling methodologies are discussed in brief.

2.2 Advantages of PLC

Since late 1980's, vast research is being carried out in the field of PLC. Due to its numerous benefits, PLC is being looked over as a strong substitute for dedicated communication infrastructure at home premises. Following are the key advantages of PLC [10]:

1. Existence of infrastructure is the key benefit of PLC. PLC is very cost effective since there is no need of installing a dedicated communication infrastructure.
2. PLC can practically reach almost everywhere in the world which makes it best suited for applications like data and voice communication.
3. PLC can serve as effective substitute for DSL in the areas where installation of DSL is a challenge.
4. Since the electricity cables exist everywhere, PLC makes internet accessible from every room through every socket.

2.3 Applications of PLC

Power Line Communication is a part of smart grid technology. It exists at various levels of to establish wired communication between different domains of smart grid. Low voltage (LV) PLC is used at customer premises as a last mile communication to communicate with other domains while Medium voltage (MV) PLC is used at distribution domain to establish communication between distribution and transmission domain. Existence of PLC at various levels of smart grid enables following applications [11].

2.3.1 Advanced Metering Infrastructure (AMI)

AMI provides users with smart metering devices at home premises. The automated metering may include metering of electricity, water and gas which is called as a smart community trial. Any appliance with smart chip can be connected to automatic metering infrastructure. The chips installed in smart appliances enable remote control and management. Home network control terminal collects data and communicates it with utility companies using AMI which provide functions like real time pricing, Demand Response implementation, monitoring and control.

AMI has following key features which makes it a better metering technology

- AMI gathers power loss information which can be used to locate and isolate faults. Once located, faults can be easily restored.
- The data collected by AMI is very accurate. Such data can be utilized for planning and analysis of the distribution system.
- Forecasting of energy availability can be done based on collected data. AMI thus can help emergency load shedding.

2.3.2 Demand Response (DR) Management

Demand response management system has the ultimate goal of minimizing the power consumption by customers. DR management is achieved by agreement between utility companies and customers. Distributed energy resources temporarily support the electricity demand at the time of energy shortage and contribute to DR management [11].

DR system is mainly based on the communication between market and customer domain. Depending upon the data collected, it varies the electricity consumption temporarily. Utility companies get additional time due to the delayed consumption and can start some additional power plants to support the energy demand. Direct Load Control (DLC) is also used for DR management. In DLC, customer makes an agreement with utility company which permits utility company to manage and control some of the home appliances. The energy consumption by appliances like air conditioner, refrigerator, electric pumps, lighting etc. is controlled remotely.

Customers also have a role to play in DR management. They can use smart appliances to communicate with smart meters and can manage their own energy usage. Smart pricing provides metering information to customers and encourages individual load management. Customers can also install DERs at home premises to support DR management [1].

2.3.3 Wide Area Situational Awareness (WASA)

The WASA system collects large amount of information about the current state of the power grid over a wide area from electric substations and power transmission lines. This information is used for monitoring (Wide Area Monitoring Systems WAMS), control (Wide Area Control Systems WACS) and protection (Wide Area Protection Systems WAPS).

Following are the features of WASA system [1]

- Phase measurement units are used to gather real time information. Control centres analyse this information and estimate the current state of the system.
- The analysis of real time information also enables prediction of system instability.
- WASA has ability to predict any future disturbances based on the gathered information. It helps to avoid occurrence of blackouts.
- Estimation and prediction gives improved control of the power system.

2.3.4 Home Energy Management System (HEMS)

HEMS controls the energy usage by setting threshold limit on the energy consumption. The threshold value is decided by real−time pricing information collected by smart meters and consumption history. HEMS is integrated with HAN which provides a channel for interaction between consumer and electrical grid [1].

HEMS resides in smart meters. All the real−time pricing information collected by smart meters is also accessed by HEMS. Whenever a price event occurs (i.e. whenever consumption exceeds a pre-decided threshold value), a signal is sent to smart appliances. The smart appliances indicate the occurrence of price event to end consumer. A delayed start is also recommended by smart appliance. Now the consumer can make a choice whether to initiate delayed start or to run normal operating mode.

2.4 PLC channel modelling approaches

As mentioned earlier, there are two modelling approaches. These approaches are described below [9], [12]:

2.4.1. Top-down approach

Top-down modelling approach is based on measurements of channel. These measurements may include transfer function measurement, channel impedance measurement. The algorithm used for this type of modelling is comparatively simpler due to the fact that it requires less computation. But since the model is completely dependent on measurements, it is prone to measurement errors and it heavily relies on accuracy of algorithm.

2.4.2 Bottom-up approach

Bottom-up modelling approach is based on mathematical calculations and channel topology. It is a deterministic modelling approach. The channel parameters like characteristic impedance and propagation constants are calculated initially. Then these calculated values are used to derive transfer function on the channel. Though this approach is more accurate, it involves complex computations. In the present thesis, Bottom-up approach is followed. Bottom-up modelling can be followed in two possible approaches. In both the approaches, two-wire transmission line channel topology as shown in Figure 2.1 is used [13].

In first approach, multipath effects of signal propagating from transmitter to receiver are considered. The reflection and transmission coefficients at each node of the topology are calculated. In second approach, ABCD parameters are used for transfer function modelling. Input and output impedances are also considered, but multipath effects are not considered.

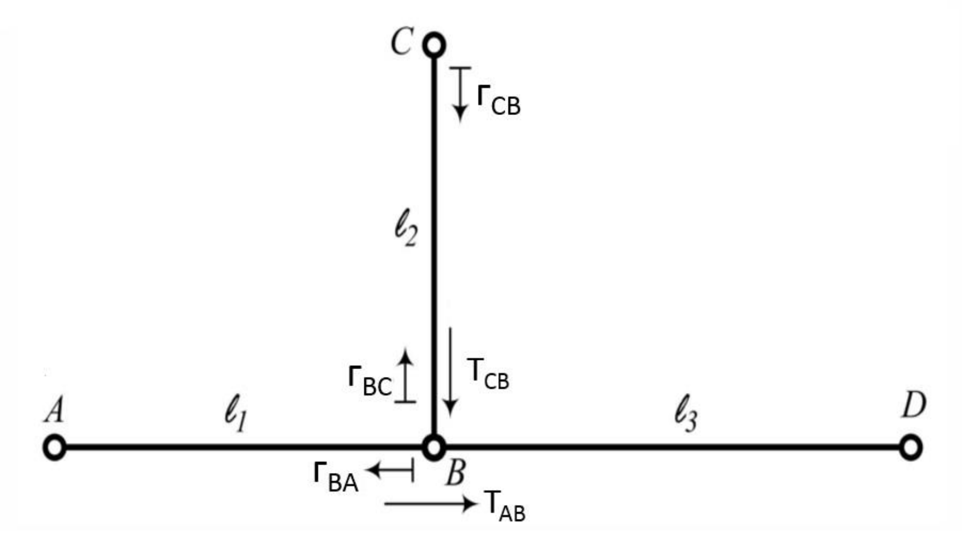


Figure 2.1: Transmission line model for PLC

In Figure 2.1, A is transmitter and D is receiver. A branch exists at node B which is terminated at node C. 'T' represents transmission coefficients while Γ represents reflection coefficients. 'ℓ ' represents length of transmission line. In present thesis, two bottom-up approaches are followed to model PLC channel and the results are compared. Both the approaches are discussed in details in following chapters.

Modelling Approach 1: Multipath modelling approach

Modelling Approach 2: ABCD parameter modelling approach

CHAPTER 3

PLC MODELLING APPROACH 1

3

PLC MODELLING APPROACH 1

3.1 PLC Channel Transfer Function

Channel modelling requires knowledge of three parameters namely attenuation, delay and reflection/transmission coefficients. As discussed in section 2.4, in bottom-up approach, these parameters are evaluated mathematically. Based on evaluated values of parameters, a channel model is built. Equation (3.1) is the basis of PLC channel modelling [6] [14].

$$H(f) = \sum_{i=1}^{N} g_i . A(f, d_i)\, e^{-j2\pi f \tau_i} \ldots (3.1)$$

Here $A(f, d_i)$ is attenuation which depends upon frequency 'f' and length of propagation 'd_i'.

While modelling a PLC channel, two parameters are primarily considered namely attenuation of signal during the propagation and the delay that signal undergoes. A weighing factor which considers transmission and reflection effects of transmission line is also taken into account in PLC channel transfer function H (f). Equation (3.2) represents a channel model for power line [14].

$$H(f) = \sum_{i=1}^{N} g_i . e^{-(\alpha_0+\alpha_1 f^k).d_i}\, e^{-j2\pi f \tau_i} \ldots (3.2)$$

Where

g_i is weighing factor

$e^{-(\alpha_0+\alpha_1 f^k).d_i}$ accounts for attenuation

$e^{-j2\pi f (d_i/v_p)}$ accounts for delay.

N is number of dominant paths and α_0, α_1, k are cable parameters. These parameters mainly depend upon the type of material used in cable and its geometry.

3.2 Multipath Modelling Approach

In order to understand the multipath propagation in PLC, a T network is considered. In Figure 3.1, A is transmitter and D is receiver. The channel has a branch at point B. The branch terminates at point C. ℓ_1, ℓ_2, ℓ_3 are cable lengths and Z_1, Z_2, Z_3 are characteristic impedance of the line. Γ_{BA}, Γ_{BC}, Γ_{CB} are reflection coefficients and T_{AB}, T_{CB} are transmission coefficients. The channel topology in Figure 3.1 is used to understand the signal propagation from transmitter A to receiver D and its multipath effects [14].

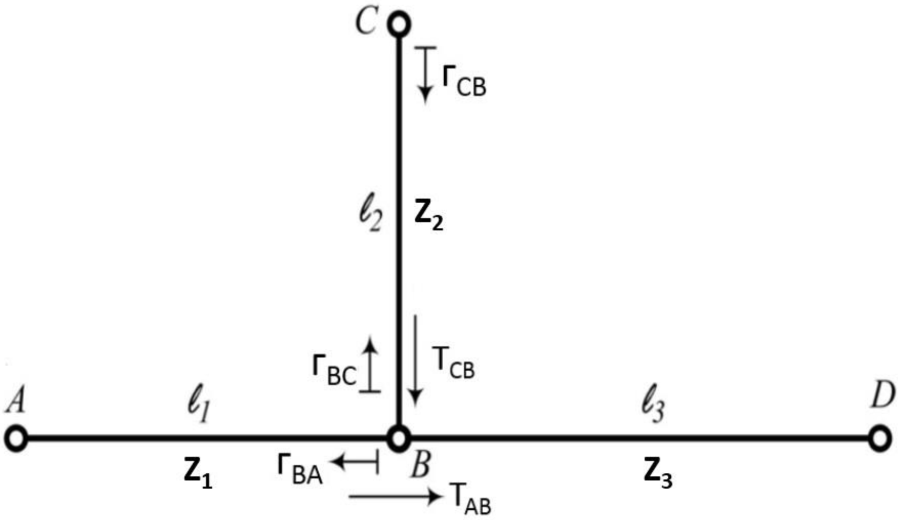


Figure 3.1: PLC channel topology

The signal propagates from A to D in two different ways. One is a direct path from A over B to D. Another path is A→B→C→D. Here the signal reflects at point C. All further waves travel from A to B and undergo multiple reflections at C before reaching D. So practically there are infinite different paths from transmitter to receiver. Each path has weighing factor g_i which is a product of reflection and transmission coefficients along that path. Higher the reflections and transmissions, smaller will be the factor g_i. Mathematically

$$|g_i| \leq 1 \ldots (3.3)$$

Also each path experiences different delay T_i defined as:

$$\mathrm{T}_i = \frac{d_i \sqrt{\epsilon_r}}{C_0} = \frac{d_i}{v_p} \ldots (3.4)$$

Where d_i is the length of the path, V_p is the phase velocity of electromagnetic wave, ε_r is dielectric constant of insulating material and C_0 is speed of light. For analyzing the PLC channel, we consider only first 'N' dominant paths.

3.3 Transmission over Power Line Channels

The signal, while traveling from A to D, undergoes multiple reflections. The reflection and transmission coefficients can be evaluated using following set of formulae [13].

$$T_{AB} = \frac{2Z_{B23}}{Z_{B23} + Z_1} \quad \dots (3.5) \qquad\qquad T_{CB} = \frac{2Z_{B13}}{Z_{B13} + Z_2} \quad \dots (3.6)$$

$$\gamma_{AB} = \frac{Z_{B23} - Z_1}{Z_{B23} + Z_1} \quad \dots (3.7) \qquad\qquad \gamma_{BC} = \frac{Z_{B13} - Z_2}{Z_{B13} + Z_2} \quad \dots (3.8)$$

$$\gamma_{CB} = \frac{Z_C - Z_2}{Z_C + Z_2} \dots (3.9)$$

Where

$$Z_{B13} = \frac{Z_1 Z_3}{Z_1 + Z_3} \dots (3.10) \qquad and \qquad Z_{B23} = \frac{Z_2 Z_3}{Z_2 + Z_3} \dots (3.11)$$

Following table describes possible paths and their corresponding reflection coefficient and length of propagation.

	Signal propagating nodes	**Reflection factor**	**Length of propagation**
1	A → B → D	T_{AB}	$l_1 + l_3$
2	A → B → C → B → D	$T_{AB}\ \Gamma_{CB}\ T_{CB}$	$l_1 + 2l_2 + l_3$
3	A → (B → C →)^2 B → D	$T_{AB}\ \Gamma^2_{CB}\ \Gamma_{BC}\ T_{CB}$	$l_1 + 4l_2 + l_3$
. **.**	. .	. .	. .
N	A → (B → C →)^N B → D	$T_{AB}\ \Gamma^{N-1}_{CB}\ \Gamma^{N-2}_{BC}\ T_{CB}$	$l_1 + 2(N-1)l_2 + l_3$

Table 3.1: Possible multipaths in PLC topology

In Table 3.1, all the 'N' possible paths are listed along with their respective reflection factors (g_i) and lengths of propagation (d_i).

If we consider path 2, which is A → B → C → B → D, the signal will flow from A to B. It will undergo reflection at node C. So the signal will traverse path CB twice and will reach receiver end ultimately. So the path lengths traversed by signal are AB + BC + CB + BD which results in length of propagation (d_i) = $l_1 + 2l_2 + l_3$. The reflection coefficient at node C and transmission coefficients of paths AB & BD will contribute to reflection factor. Hence reflection factor (g_i) = $T_{AB}\ \Gamma_{CB}\ T_{CB}$. Similarly g_i and d_i are calculated for all 'N' paths.

3.4 PLC Channel Response

MATLAB simulation was carried out to plot the transfer function of PLC channel [15]. Following parameters were considered for the simulation with Terminal C left open. Lengths are l_1=15m; l2=10m; l_3=15m. Characteristics Impedance are Z_1=Z_2=Z_3=100Ω.

Then considering N = 4 dominant paths, we calculated following coefficients:

	Reflection coefficient	**Length of propagation (in m)**
1	0.6666	30
2	0.4444	50
3	-0.1480	70
4	0.0494	90

Table 3.2: Channel parameters for N = 4

Simulation for first 10 dominant paths was also carried out which yielded similar results in terms of channel parameters. Using the above obtained channel parameters, amplitude and phase of the PLC channel transfer function were plotted in a frequency range of 0 – 20 MHz.

Figure 3.2 shows the amplitude and phase plots for N = 4 and N = 10 dominant paths respectively.

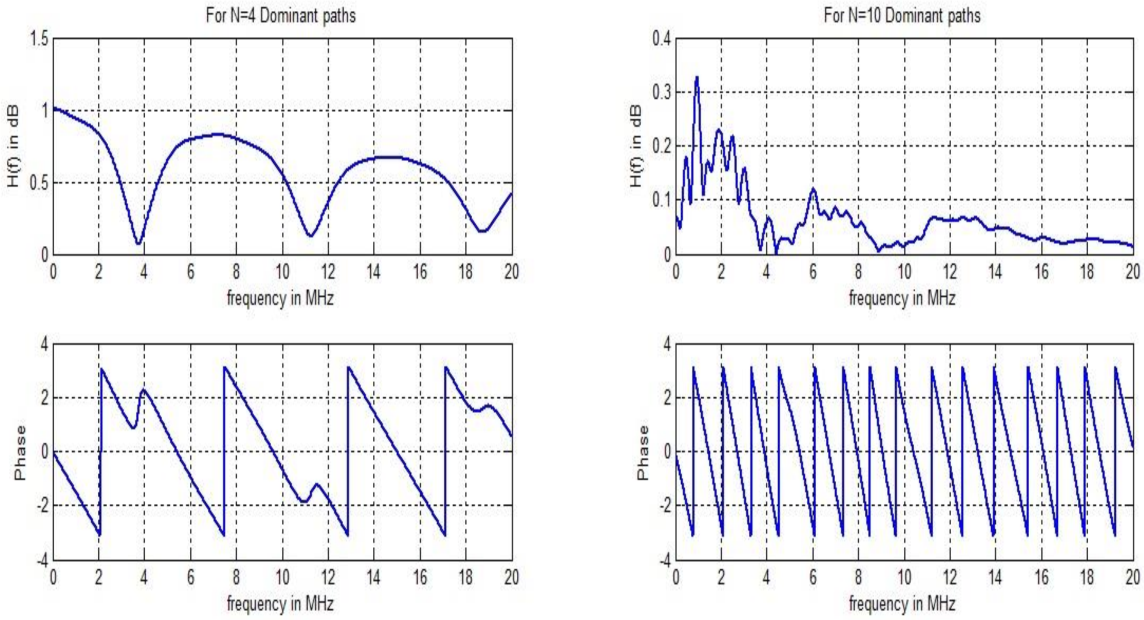


Figure 3.2: PLC amplitude and phase plots for N=4, 10

3.5 PLC Channel Analysis

In the present section, the PLC channel modelled in section 3.4 is analyzed for various topological conditions [16]. The conditions are as follows:

1. Length between transmitter and receiver
2. Length of branch
3. Terminating impedance of branch

Above three are the topological conditions for which the PLC channel is analyzed. In each case, effects of variations in each of these conditions is observed by plotting amplitude response in the range 0 – 20 MHz.

3.5.1 Effect of length between transmitter and receiver

First physical parameter is the length of cable between transmitter (A) and receiver (D). In this case, the distance between transmitter and receiver is varied keeping all other parameters constant. PLC model in Fig. 1 is used. Length between A and D is varied from 30m to 200m while l_2=10m is kept constant. Under all circumstances, branching point B is connected at the midpoint. Characteristics impedance are $Z_1=Z_2=Z_3=100\Omega$. Terminal C is kept open.

4 cases are observed: $l_{(AtoD)}$ = 30m, 50m, 100m and 200m.

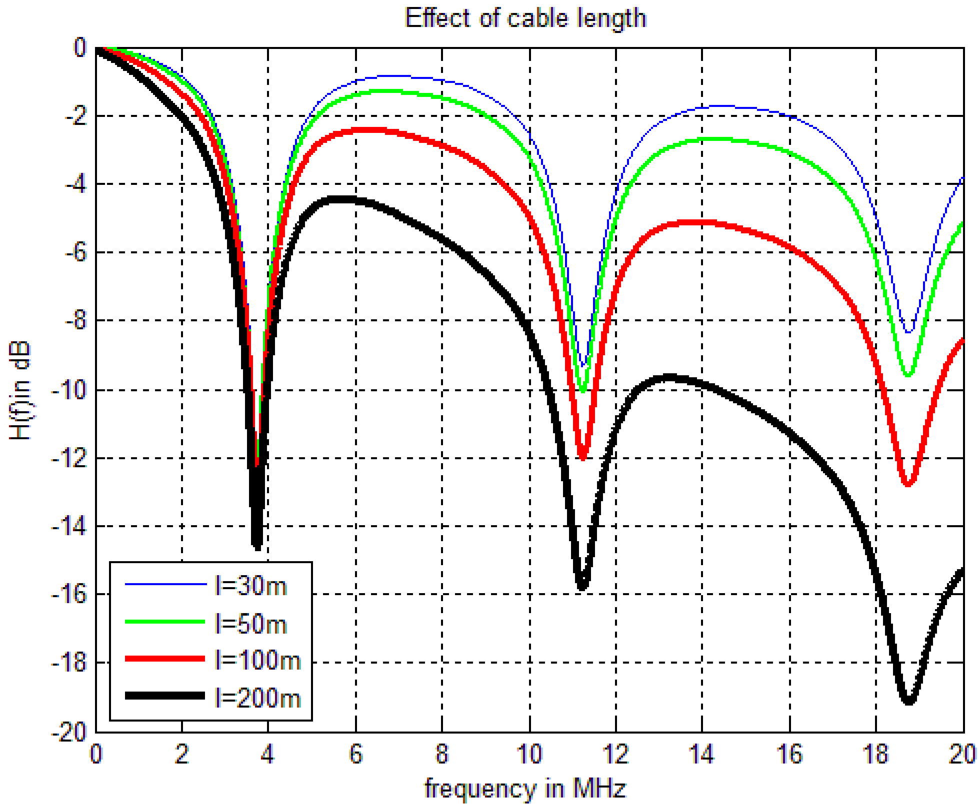


Figure 3.3: Effect of cable length between transmitter and receiver

From Figure 3.3, we can observe that as the length between A (Transmitter) and D (Receiver) increases, the attenuation gradually increases i.e. gain of transfer function H (f) reduces. This happens because with longer cable lengths, the signal is exposed to more interference and so its strength decreases over the distance.

3.5.2 Effect of branch length

The second parameter is the length of each branch/tap. In this case, we varied the length of branch keeping all other parameters constant. Here $l_1=l_3=15m$ are kept constant. Length of branch l2 is varied from 5m to 20m. Characteristics Impedance are $Z_1=Z_2=Z_3=100\Omega$. Terminal C is kept open. 4 cases are observed: l(branch) = l_2 = 5m, 10m, 15m and 20m.

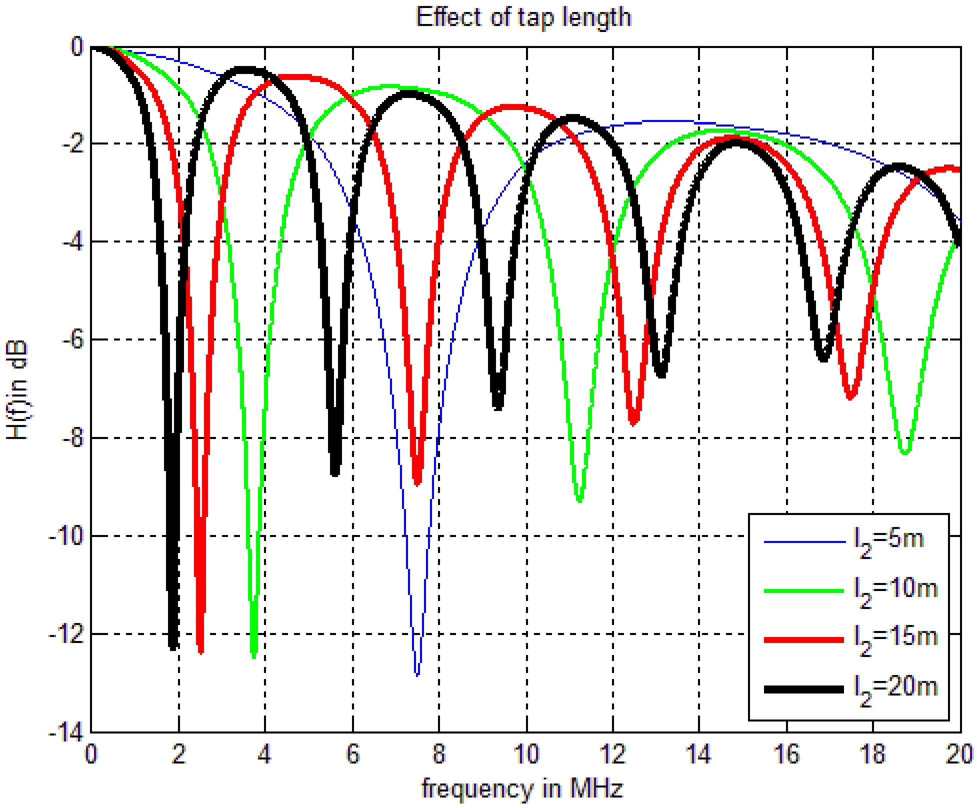


Figure 3.4: Effect of branch length

From Fig. 3.4, we observed that number of notches changes with the length of branch. For l_2 = 5m, we observed only one notch while 5 notches were observed for l_2 = 20m.

The reason is as the length of tap/branch increases, delay and attenuation values for each received multipath component increases, while delay for first received component remains constant (as first path is a direct path). Any change in delay causes change in position of notches detected in transfer function H (f). Number of notches increases with increasing length of tap/branch.

3.5.3 Effect of terminating impedance of branch

The transfer function of PLC channel also depends upon the impedance with which the branch is terminated. So branch impedance was varied and other parameters were kept constant. Let Z_C be characteristic impedance and Z_b be the terminating impedance of the branch. There are three possible cases:

a. Z_b is less than Z_C
b. Z_b is greater than Z_C
c. $Z_b = Z_C$, perfectly matched condition

In all three cases, we considered $Z_C = 100$. Lengths of cable $l_1=l_3=15$m are kept constant. Length of branch $l_2=10$m is also kept constant. Initially terminal C was left open. Now it is terminated by an impedance Z_b.

3.5.2 (a) Z_b is less than Z_C

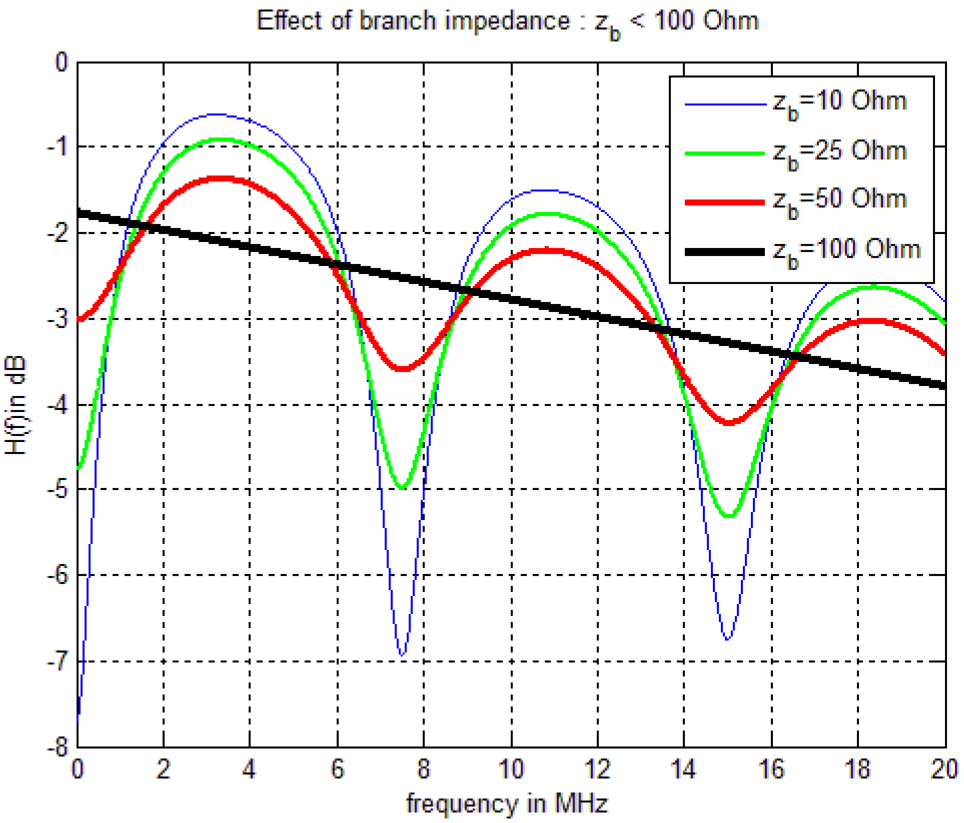


Figure 3.5: Effect of terminating impedance of branch ($Z_b < Z_C$)

From Fig. 3.5, we observed that depth of notches is changing while the number of notches remains unchanged. Since reflection coefficient Γ_{CB} decreases as the branch impedance increases towards Z_C, reflected multipath components attenuate more. Thus, weak multipath components will be received. This leads to a decrement in the depth of the notches in transfer functions.

3.5.2 (b) Z_b is greater than Z_0

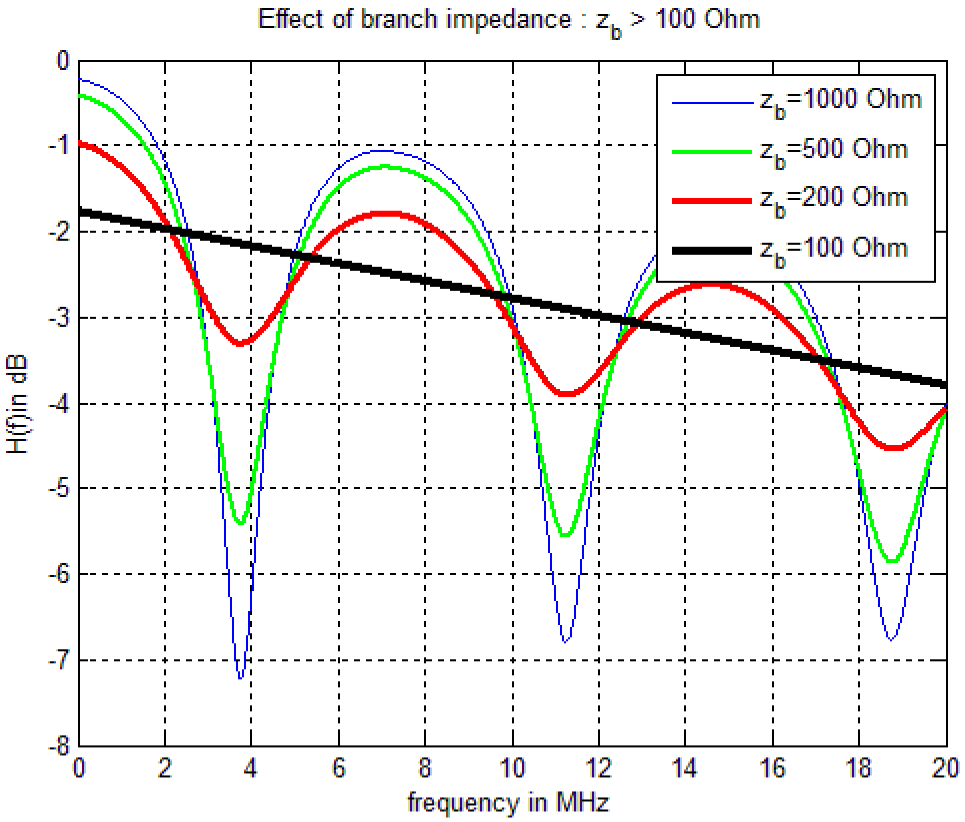


Figure 3.6: Effect of terminating impedance of branch ($Z_b > Z_C$)

Form Fig. 3.6, we can observe change in depth of notches. Since reflection coefficient Γ_{CB} increases as the branch impedance tends to be greater values than Z_C, reflected multipath components attenuate less. Thus, stronger multipath components are received. This leads to an increment in the depth of the notches in transfer functions.

3.5.2 (c) $Z_b = Z_0$, perfectly matched condition

In both cases we observed that at $Z_b = Z_C = 100\Omega$, we get $\Gamma_{CB} = 0$. So it is a perfectly matched condition and no reflection will occur at branch impedance. Thus in Figure 3.5 and Figure 3.6, a straight line can be observed indicating a perfect match.

CHAPTER 4

PLC MODELLING APPROACH 2

4

PLC MODELLING APPROACH 2

4.1 PLC Transmission line Model

PLC modelling approach 2 is based on ABCD parameters of the channel. A two-wire transmission line model is considered with source impedance Z_S, load impedance Z_L and branch terminating impedance Z_b. In Figure 4.1, d_1, d_2 and d_b are the lengths of transmission line sections. V_S is source/excitation [17].

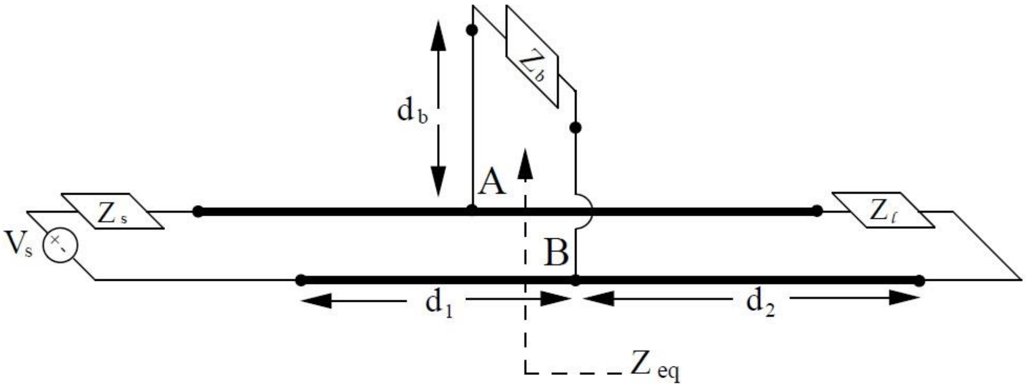


Figure 4.1: Two-wire transmission line model

For analysis convenience, the channel model shown in figure 4.1 can be simplified as shown in figure below [17].

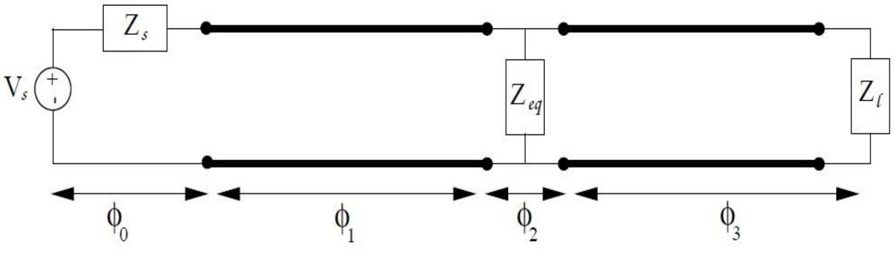


Figure 4.2: Simplified model

4.1.1 ABCD parameters of transmission line

For a transmission line with length L, characteristic impedance Z_C and propagation constant γ, the ABCD matrix is defined as follows [17] [18].

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cosh(\gamma l) & Z_C \sinh(\gamma l) \\ {}^{1}/_{Z_C} \sinh(\gamma l) & \cosh(\gamma l) \end{bmatrix} \quad \ldots (4.1)$$

Where

$$Z_C = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \quad \ldots (4.2) \qquad and \qquad \gamma = \sqrt{(R + j\omega L)(G + j\omega C)} \quad \ldots (4.3)$$

For a transmission line with a serially connected load Z_S

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & Z_S \\ 0 & 1 \end{bmatrix} \quad \ldots (4.4)$$

For a transmission line with a load Z_P connected in parallel

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ {}^{1}/_{Z_P} & 1 \end{bmatrix} \quad \ldots (4.5)$$

For a bridge tap/branch terminated with load impedance Z_b

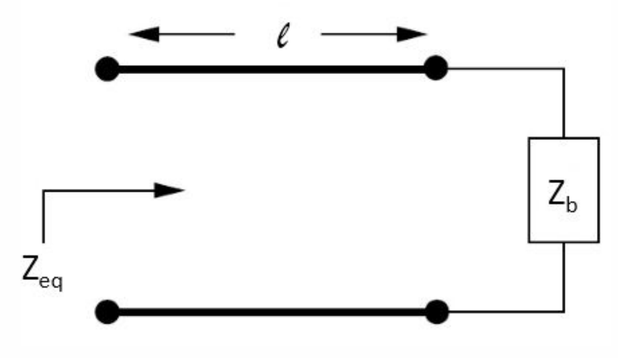


Figure 4.3: Transmission line with branch impedance Z_b

The equivalent impedance Z_{eq} is [19]

$$Z_{eq} = Z_C \frac{Z_b + Z_C \tanh(\gamma l)}{Z_C + Z_b \tanh(\gamma l)} \quad \ldots (4.6)$$

Equations (4.1) – (4.6) can be used to evaluate ABCD parameters of the transmission line model shown in figure 4.2.

4.1.2 Calculation of ABCD parameters

In Figure 4.2, the channel is divided in four sections namely ϕ$_0$, ϕ$_1$, ϕ$_2$ and ϕ$_3$ for simplicity. For evaluating ABCD parameters of the channel, the ABCD parameters of each section are calculated independently. Then the overall ABCD matrix will be the multiplication of individual ABCD matrices [20].

Section ϕ$_0$ is a load in series. Thus the ABCD parameters for this section are calculated using equation (4.4) [12].

$$\emptyset_0 = \begin{bmatrix} 1 & Z_S \\ 0 & 1 \end{bmatrix} \quad \dots (4.7)$$

Equation (4.1) is used to calculate ABCD parameters for sections ϕ$_1$ and ϕ$_3$.

$$\emptyset_1 = \begin{bmatrix} \cosh(\gamma_1 l_1) & Z_1 \sinh(\gamma_1 l_1) \\ {}^1/_{Z_1} \sinh(\gamma_1 l_1) & \cosh(\gamma_1 l_1) \end{bmatrix} \quad \dots (4.8)$$

$$\emptyset_3 = \begin{bmatrix} \cosh(\gamma_2 l_2) & Z_2 \sinh(\gamma_2 l_2) \\ {}^1/_{Z_2} \sinh(\gamma_2 l_2) & \cosh(\gamma_2 l_2) \end{bmatrix} \quad \dots (4.9)$$

Section ϕ$_2$ is a load in parallel. Thus the ABCD parameters for this section are calculated using equation (4.5).

$$\emptyset_2 = \begin{bmatrix} 1 & 0 \\ {}^1/_{Z_{eq}} & 1 \end{bmatrix} \quad \dots (4.10)$$

From equations (4.7) – (4.10), the overall ABCD matrix for PLC channel is given as:

$$\emptyset = \prod_{i=0}^{3} \emptyset_i = \emptyset_0 \emptyset_1 \emptyset_2 \emptyset_3 = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \quad \dots (4.11)$$

Using equations (4.7) – (4.10), in equation (4.11), we get

$$\emptyset = \begin{bmatrix} 1 & Z_S \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \cosh(\gamma_1 l_1) & Z_1 \sinh(\gamma_1 l_1) \\ {}^1/_{Z_1} \sinh(\gamma_1 l_1) & \cosh(\gamma_1 l_1) \end{bmatrix} \begin{bmatrix} 1 & 0 \\ {}^1/_{Z_{eq}} & 1 \end{bmatrix} \begin{bmatrix} \cosh(\gamma_2 l_2) & Z_2 \sinh(\gamma_2 l_2) \\ {}^1/_{Z_2} \sinh(\gamma_2 l_2) & \cosh(\gamma_2 l_2) \end{bmatrix}$$

The ABCD parameters so obtained are [17]

$$A = \cosh(\gamma_2 l_2)\, \alpha + \frac{\sinh(\gamma_2 l_2)\, \beta}{Z_2} \quad \dots (4.12)$$

$$B = Z_2 \cosh(\gamma_2 l_2)\, \alpha + \cosh(\gamma_2 l_2) \beta \quad \dots (4.13)$$

$$C = \cosh(\gamma_2 l_2)\,\varepsilon + \frac{\sinh(\gamma_2 l_2)\,\vartheta}{Z_2} \quad \dots (4.14)$$

$$D = Z_1 \cosh(\gamma_2 l_2)\,\varepsilon + \cosh(\gamma_2 l_2)\vartheta \quad \dots (4.15)$$

Where $\alpha, \beta, \varepsilon$ & ϑ are constants defined as follows:

$$\alpha = \cosh(\gamma_1 l_1) + \frac{Z_S}{Z_1} \sinh(\gamma_1 l_1) \quad \dots (4.16)$$

$$\beta = Z_1 sinh(\gamma_1 l_1) + Z_S \cosh(\gamma_1 l_1) \quad \dots (4.17)$$

$$\varepsilon = \frac{[Z_1 \cosh(\gamma_1 l_1) + Z_S sinh(\gamma_1 l_1) + Z_{eq} sinh(\gamma_1 l_1)]}{Z_1 Z_{eq}} \quad \dots (4.18)$$

$$\vartheta = \frac{[Z_1 sinh(\gamma_1 l_1) + Z_S cosh(\gamma_1 l_1)]}{Z_{eq}} + cosh(\gamma_1 l_1) \quad \dots (4.19)$$

4.1.3 Channel Transfer Function

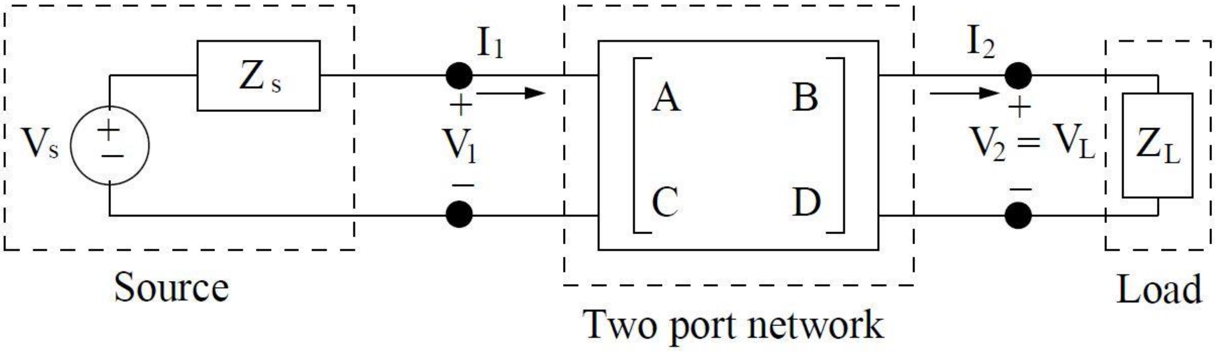


Figure 4.4: PLC channel transfer function using ABCD parameters

Figure 4.4 shows a two-port network presentation of PLC channel. From above figure, we can write:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \quad \dots (4.20)$$

Thus a PLC channel transfer function is defined as [17]

$$H(f) = \frac{V_L}{V_S} = \frac{Z_L}{AZ_L + B + CZ_L Z_S + DZ_S} \quad \dots (4.21)$$

The input impedance is defined as

$$Z_1 = \frac{V_1}{I_1} = \frac{AZ_L + B}{CZ_L + D} \quad \dots (4.22)$$

4.2 PLC amplitude and phase response

In this section, the channel modelled in section 4.1 is analysed for various conditions and the results are plotted in terms of amplitude and phase response [21].

4.2.1 Effect of length between transmitter and receiver

Here the length between transmitter and receiver ‘l’ is gradually decreased while keeping other parameters constant. Other parameters include:

1. Length of branch = l_b = 10m
2. Terminating impedance of branch = Z_b = 60Ω = characteristic impedance (Z_C).
3. Source impedance = Z_S = 50Ω.
4. Load impedance = Z_L = 50Ω.

Following are the simulation results for l = 40m, 30m, 20m and 10m.

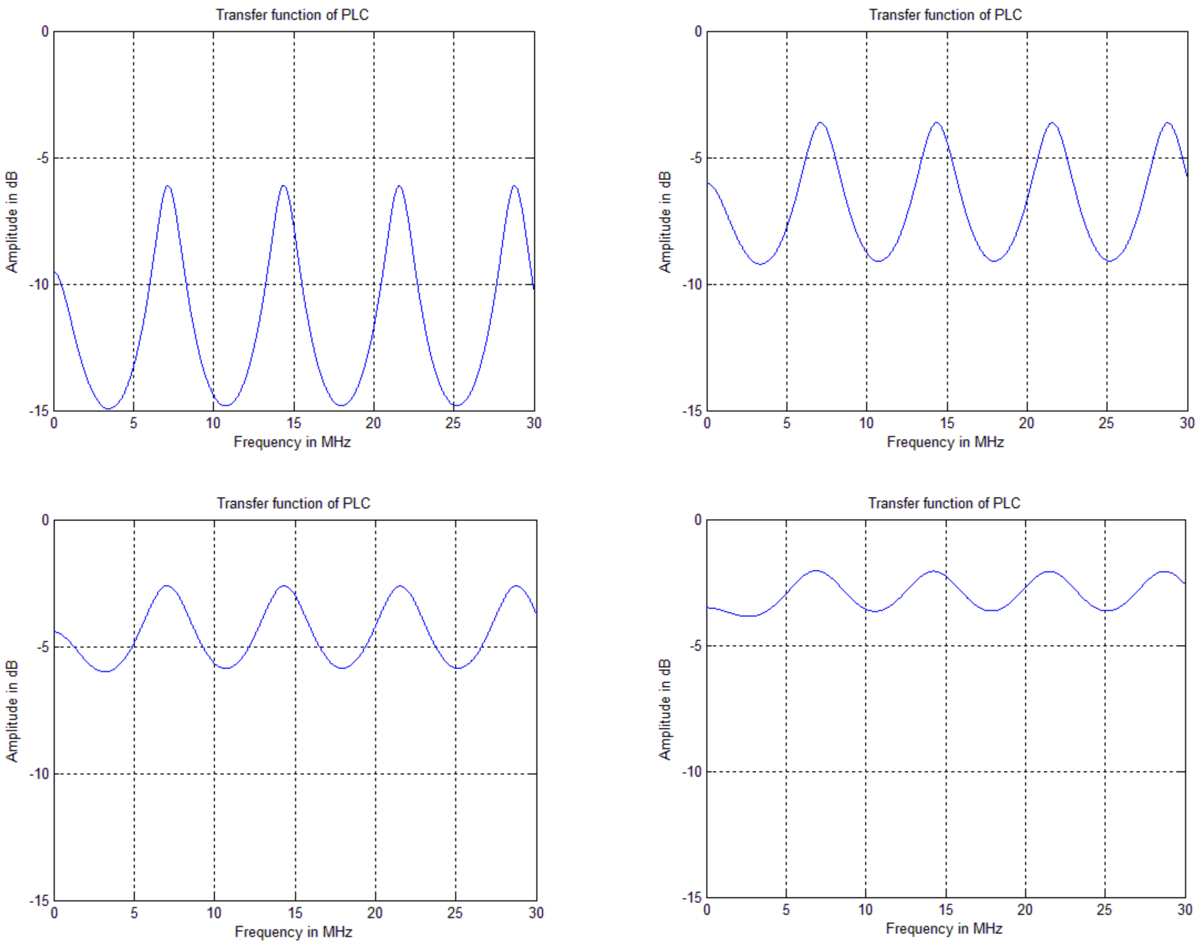


Figure 4.5: Effect of cable length between transmitter and receiver

From figure 4.5, it can be observed that as the length between transmitter and receiver decreases, the attenuation of the signal decreases. In other words, the gain of transfer function increases.

4.2.2 Effect of branch length

Here the length of branch ‘l_b’ is gradually increased while keeping other parameters constant. Other parameters include:

1. Length between transmitter and receiver = l = 20m
2. Terminating impedance of branch = Z_b = 60Ω = characteristic impedance (Z_C).
3. Source impedance = Z_S = 50Ω.
4. Load impedance = Z_L = 50Ω.

Following are the simulation results for l_b = 5m, 10m, 15m and 20m.

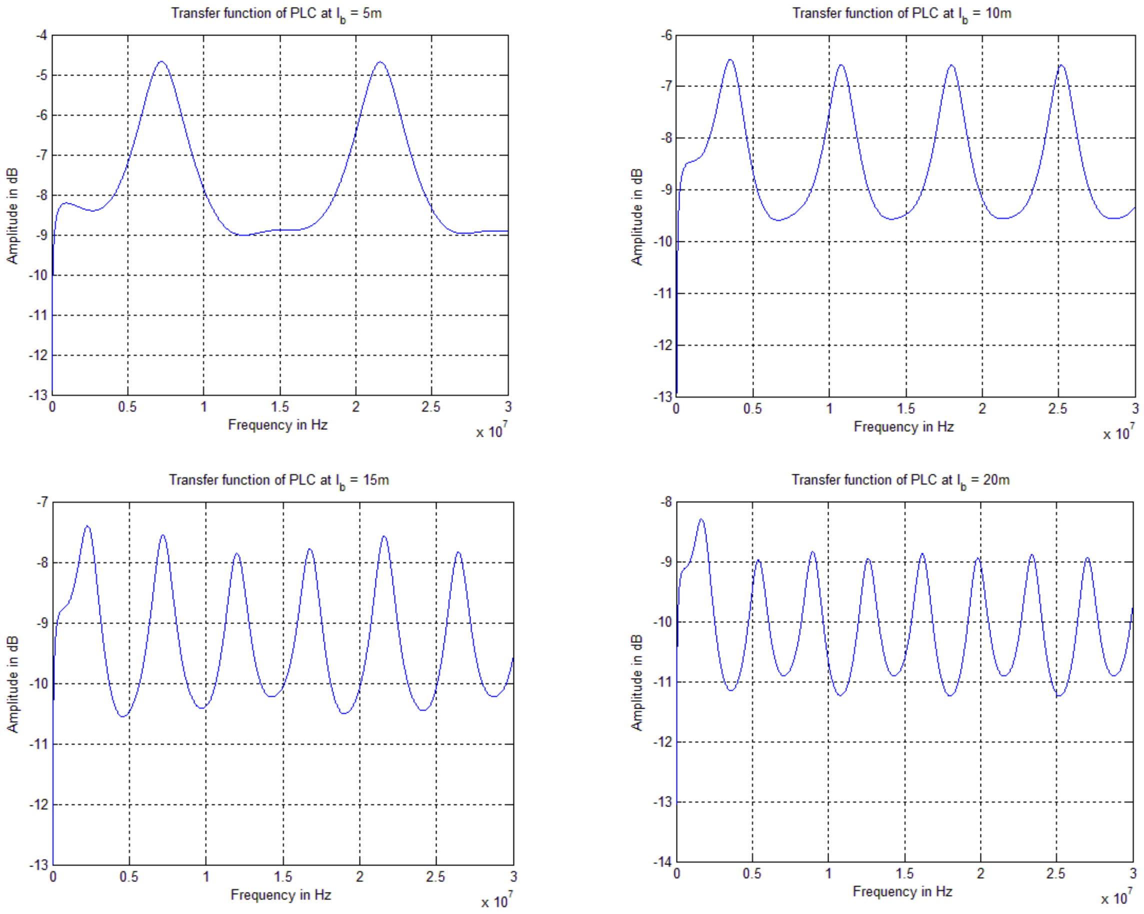


Figure 4.6: Effect of branch length

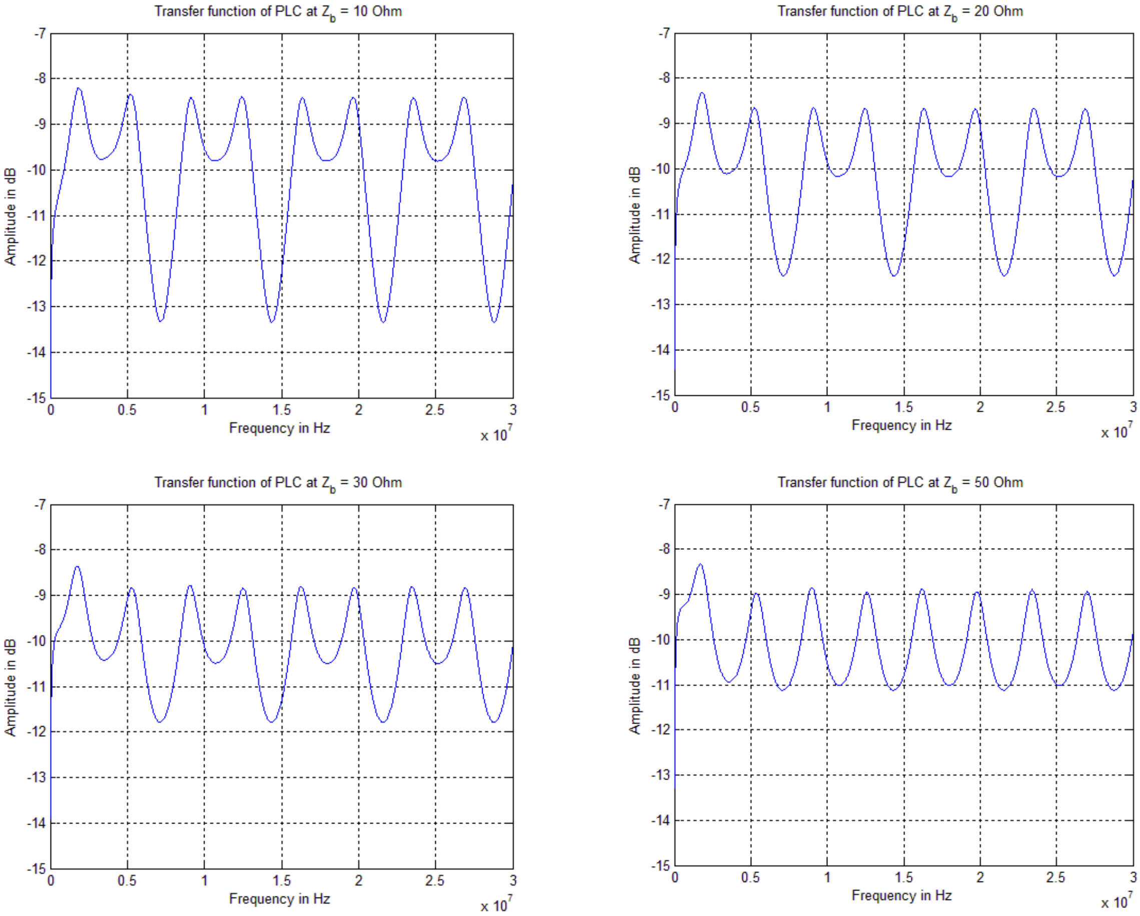
From figure 4.6, it can be observer that as the branch length increases, the number of notches increases.

4.2.3 Effect of terminating impedance of branch ($Z_b < Z_C$)

Here the terminating impedance of branch 'Z_b' is gradually increased while keeping other parameters constant. The characteristic impedance of cable is 60Ω. Other parameters include:

1. Length between transmitter and receiver = l = 20m
2. Length of branch = l_b = 10m
3. Source impedance = Z_S = 50Ω.
4. Load impedance = Z_L = 50Ω.

Following are the simulation results for Z_b = 10Ω, 20Ω, 30Ω and 50Ω.



Transfer function of PLC at Z_b = 10 Ohm

Transfer function of PLC at Z_b = 20 Ohm

Transfer function of PLC at Z_b = 30 Ohm

Transfer function of PLC at Z_b = 50 Ohm

Figure 4.7: Effect of terminating impedance of branch ($Z_b < Z_C$)

From figure 4.7 it can be observed that, as the terminating impedance Z_b increases towards Z_C, the depth of notches decreases. It is because in this case, the impedance Z_b is approaching the characteristic impedance of cable Z_C. When it will cross the value Z_C, the depth of notches will again increase.

4.2.4 Effect of terminating impedance of branch ($Z_b > Z_C$)

Here also the terminating impedance of branch 'Z_b' is gradually increased while keeping other parameters constant. But in this case, the value of Z_b is greater than Z_C. The characteristic impedance of cable is $Z_C = 60\Omega$. Other parameters include:

1. Length between transmitter and receiver = $l = 20m$
2. Length of branch = $l_b = 10m$
3. Source impedance = $Z_S = 50\Omega$.
4. Load impedance = $Z_L = 50\Omega$.

Following are the simulation results for $Z_b = 70\Omega$, 80Ω, 100Ω and 120Ω.

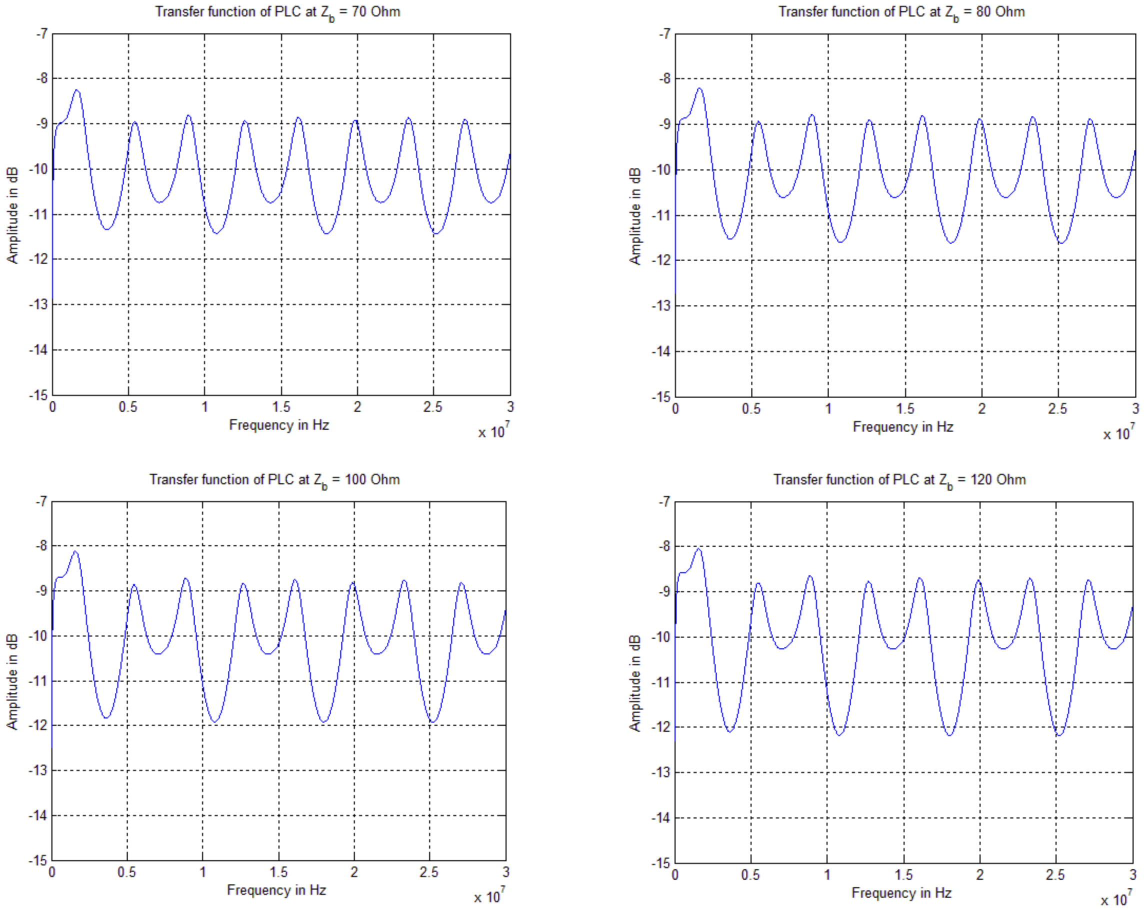


Figure 4.8: Effect of terminating impedance of branch ($Z_b > Z_C$)

From figure 4.8 it can be observed that, as the value of terminating impedance Z_b increases away from Z_C, the depth of notches increases.

4.3 Comparison of different modelling approaches

In chapter 3, a multipath channel modelling approach was discussed followed by chapter 4 wherein a PLC channel model based on ABCD parameters is discussed in details. The results were obtained in terms of amplitude and phase response in both cases. The channel model is analysed in frequency range of 0–30 MH_Z. The simulations were carried out in MATLAB environment.

In both the modelling approaches, similar results were obtained. Both the models were subjected to three cases namely effect of length between transmitter and receiver, effect of branch length and effect of terminating impedance of branch. All the three cases yielded results which apparently match. Following observations were drawn after analysing three cases in both approaches:

1. Effect of length between transmitter and receiver

   Change of length between transmitter and receiver leads to change in attenuation of transfer function. With increasing length, the PLC transfer function undergoes more and more attenuation.

2. Effect of branch length

   With increasing branch length, PLC transfer function exhibits increasing number of notches. Notches are the results of signal reflection at nodes.
3. Effect of terminating impedance of branch
   a. When terminating impedance of branch (Z_b) is less than characteristic impedance (Z_C), the PLC transfer function exhibits change in depth of notches. As Z_b tends to Z_C, the depth of notches tends to reduce.
   b. When Z_b is greater than Z_C and is tending away from Z_C, then the transfer function shows increase in depth of notches.
   c. At $Z_b = Z_C$, characteristic impedance and terminating impedance of branch are perfectly matched which results in no reflection at branch node point C.

In spite of all the above mentioned observations being same in both the modelling approaches, the first approach differs from approach 2 by the fact that it considers multipath effects which makes it more fit for accurate system design. Thus in following chapters, a PLC channel model based on multipath effects is considered.

CHAPTER 5

ANALYSIS OF MULTI-BRANCH PLC TOPOLOGY

5

ANALYSIS OF MULTI-BRANCH PLC TOPOLOGY

5.1 Introduction

In the present thesis, a PLC channel topology with single branch is considered so far. But in practice, multiple branches exist for a power line channel. Thus in present chapter, a PLC channel with multiple branches is discussed in details.

Initially a topological symmetry of PLC channel is assumed for simplicity of analysis. Topological simplicity refers to a channel topology with equal length of all the branches, equal length of transmission line sections and equal branch terminating impedances [9].

Since such a topological symmetry does not exist in practical scenario, a channel topology with unequal branch lengths and branch terminating impedances is also considered in the present chapter.

5.2 PLC with topological symmetry

A topology with two branches as shown in Figure 5.1 is considered for further discussion.

Here Characteristic impedance of cable $Z_0 = 100\Omega$.

Length of cable $l_1 = l_2 = 15$m.

Length of each branch $l_3 = 10$m.

Branch load impedance $Z_b = 50\Omega$.

Here we assume that all the taps are equidistant and they are terminated by same impedance value. The same logic can be extended for number of branches more than 2.

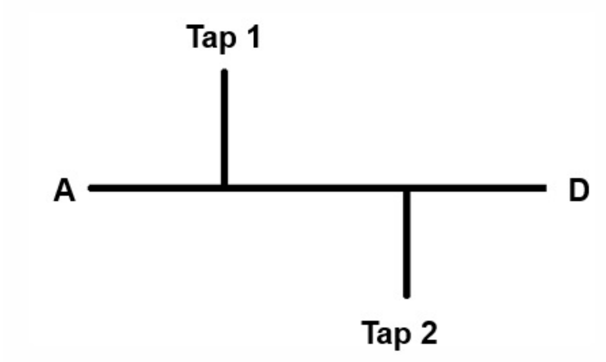


Figure 5.1: A PLC topology with two branches

The simulation was carried out to obtain the amplitude and phase response of the above topology. Figure 5.2 shows the MATLAB simulation results for PLC channel with topological symmetry with number of branches = n = 2.

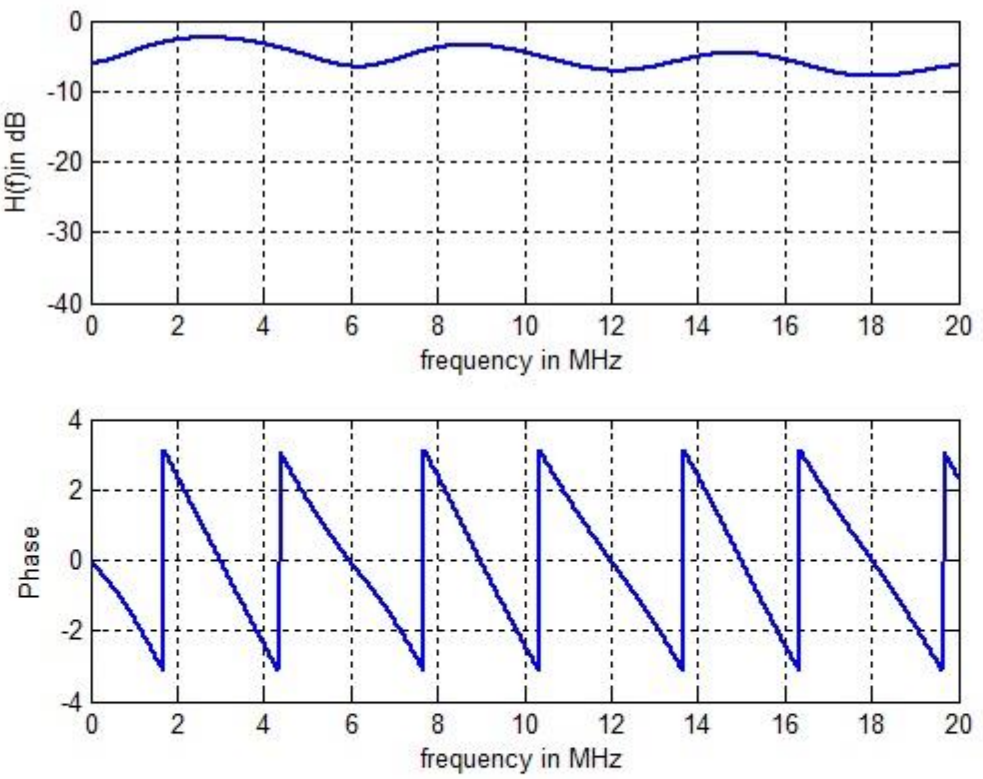


Figure 5.2: Channel response for topologically symmetrical PLC channel with 2 branches

Simulations were also carried out for number of branches greater than 2. In all the cases, topological symmetry was retained. Following are the simulation results for number of branches n = 4, 6 and 10.

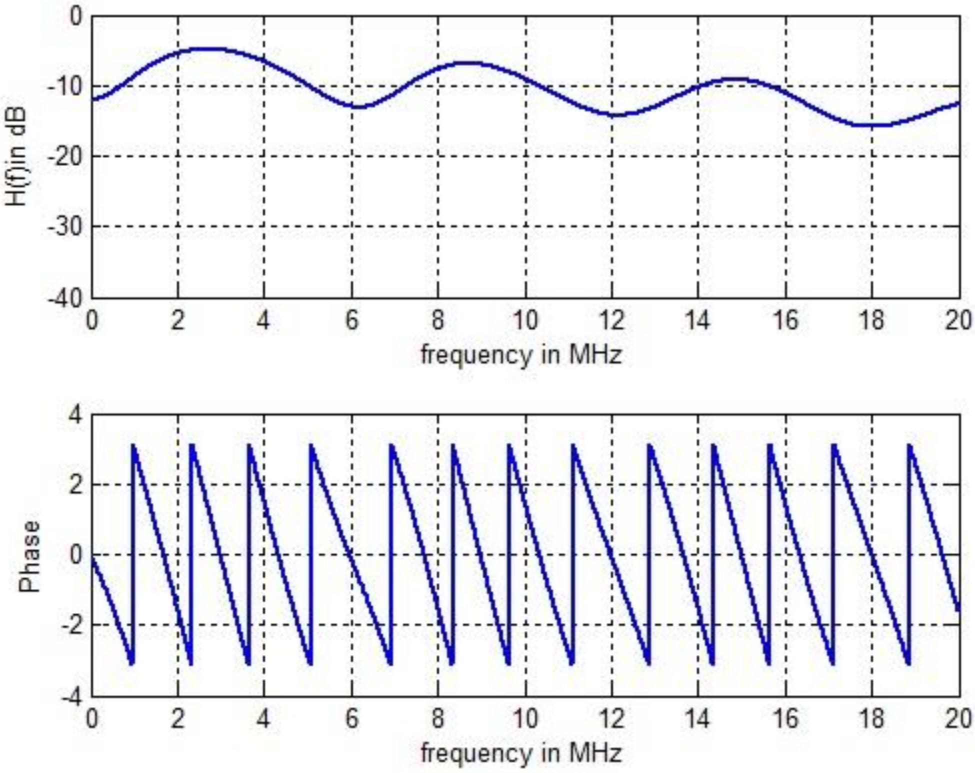


Figure 5.3: Channel response for topologically symmetrical PLC channel with 4 branches

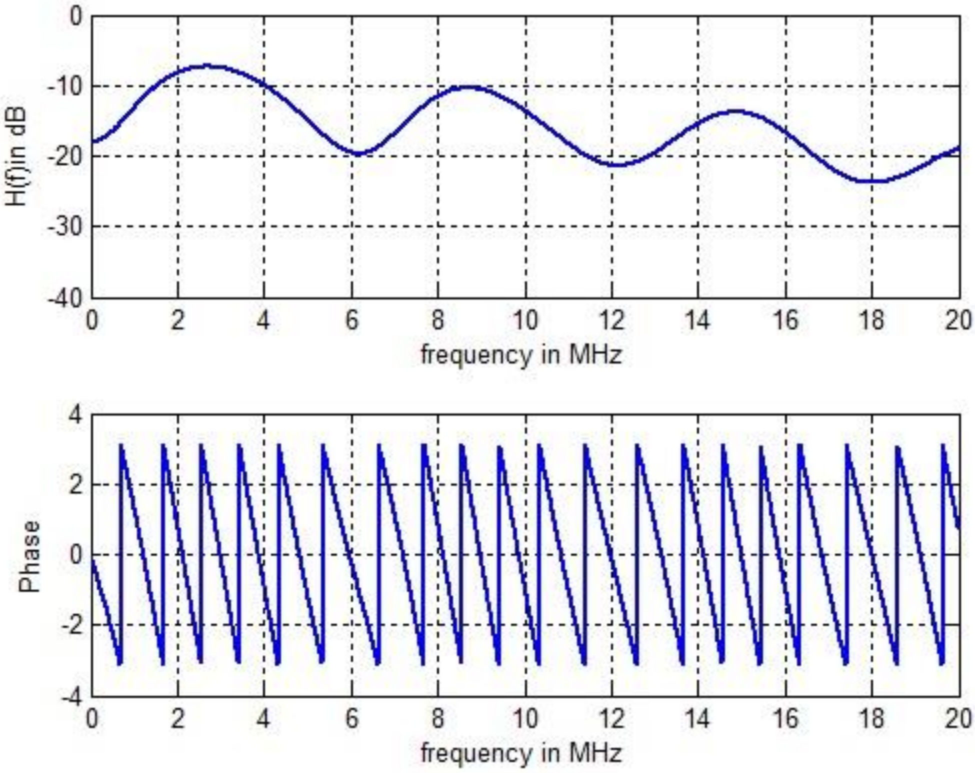


Figure 5.4: Channel response for topologically symmetrical PLC channel with 6 branches

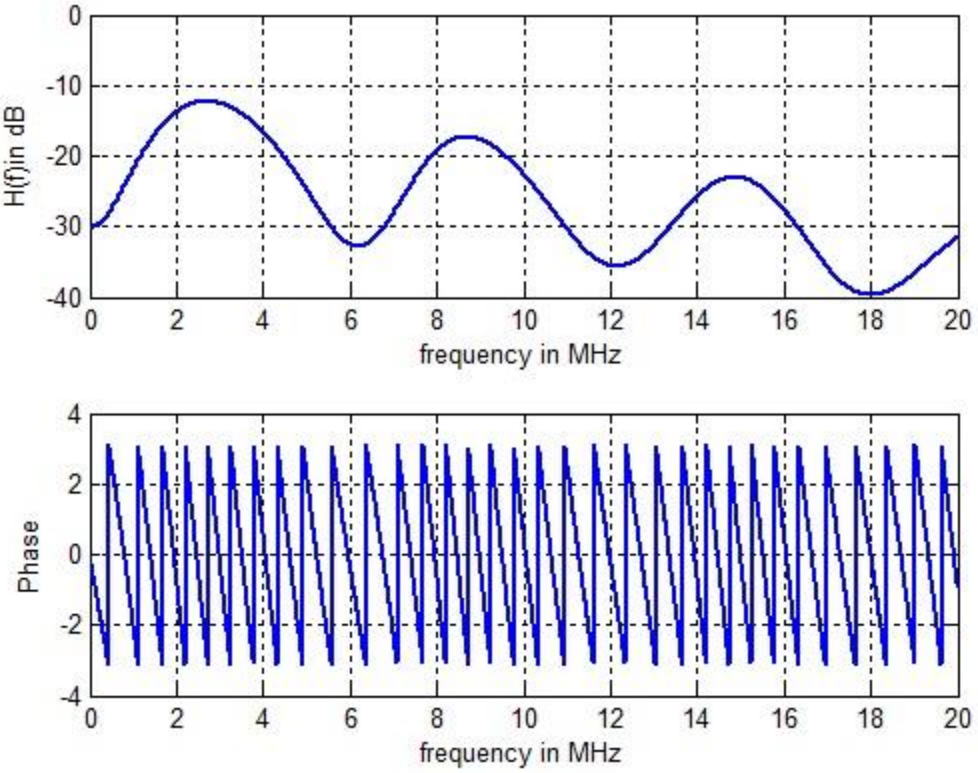


Figure 5.5: Channel response for topologically symmetrical PLC channel with 10 branches

From Figures 5.2 – 5.5, it can be concluded that as number of branches increase, the signal undergoes more reflection and thus the weighing factor g_i reduces. Hence the gain of transfer function reduces. We can observe that in all 4 cases, number of notches remains constant. It is because in all cases, length of branch is constant.

5.3 PLC with no topological symmetry

In section (IV.A), the PLC topologies with multiple branches are analysed with the primary assumption that all the taps are equidistant and they are terminated by same impedance value. But this may not be the case in practice. So we considered following topology in which taps are not equidistant.

For analysing a PLC without any topological symmetry, a PLC channel topology shown in figure 5.6 is considered. The parameters of the topology in figure 5.6 are as follows:

1. Lengths of cable are l_1 = 10m, l_2 = 15m, l_3 = 20m,
2. Lengths of branch are $l_{branch1}$ = 10m, $l_{branch2}$ = 15m.
3. Characteristic impedance are $Z_1 = Z_2 = Z_3 = 100\Omega$.

4. Branch impedances are $Z_{branch1} = Z_{branch2} = 50\Omega$.
5. Branches are terminated by $Z_{b1} = Z_{b2} = 30\Omega$.

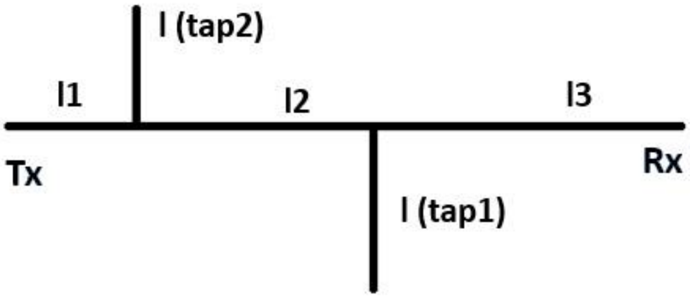


Figure 5.6: A PLC topology with Non-Equidistant Branches

Figure 5.7 shows the simulation results for PLC channel with no topological symmetry.

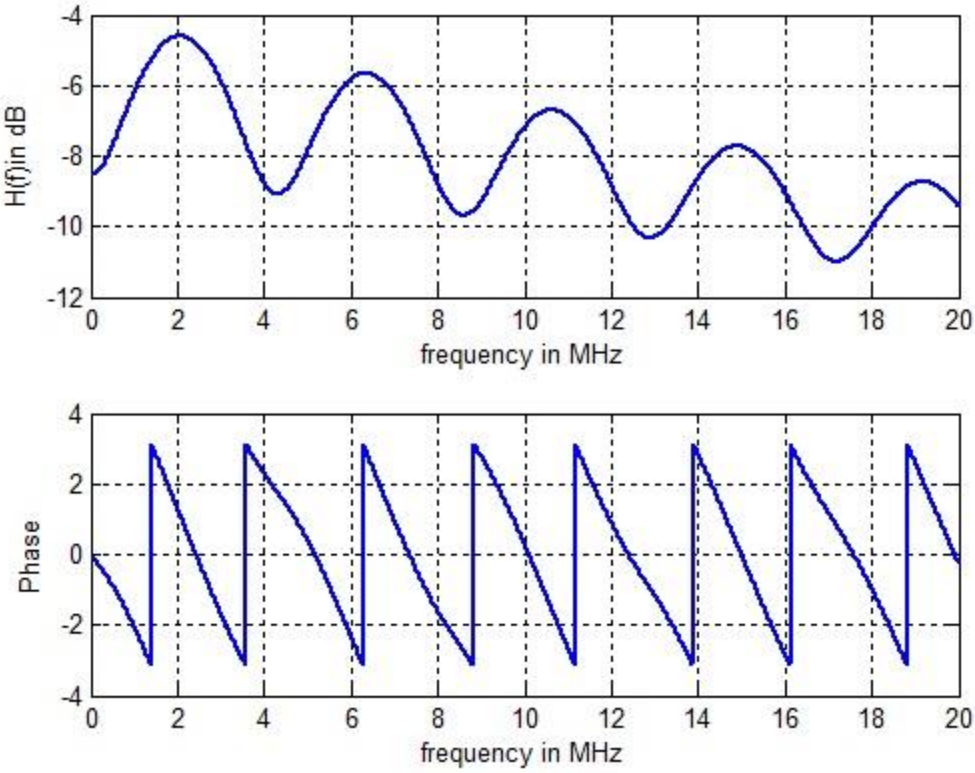


Figure 5.7: Channel response for topologically non-symmetrical PLC channel with 2 branches

In this case, the branch lengths and the characteristic impedance of the branch are different. Both the branches are terminated by impedance less than characteristic impedance. We can observe from Figure 5.7 that the transfer function exhibits more notches than the previous case.

CHAPTER 6

PERFORMANCE EVALUATION OF BROADBAND POWER LINE CHANNEL

6

PERFORMANCE EVALUATION OF BROADBAND POWER LINE CHANNEL

6.1 Introduction

An In-building power line communication is being looked upon as a strong alternative to wireless communication. Wireless communication cannot reach every corner of the building with satisfactory throughput. On the contrary, indoor PLC can reach every room, can connect every floor with reliable performance.

To improve the performance of power line channel, various modulation techniques are used. In the present thesis, an OFDM modulation scheme with BPSK and QPSK keying techniques is discussed. The performance is tested by plotting Bit Error Rate probability curve.

OFDM is a parallel transmission scheme. In OFDM, a stream of high data rate input serial data is split into a number of low data rate streams. A separate carrier is used to modulate each sub-stream. This results in reduction of bandwidth of subcarriers i.e. the bandwidth of sub-carrier becomes less than coherence bandwidth [22].

The sub-carriers chosen to modulate individual data sub-streams are completely orthogonal to each other. The fact that the subcarriers are completely orthogonal enables complete recovery of information possible by choosing correct sampling instances. Although OFDM sub-carrier spectra overlap each other, a received signal can be sampled at the instances shown in figure 6.1. The sampling instances so chosen lead to faithful recovery of entire information.

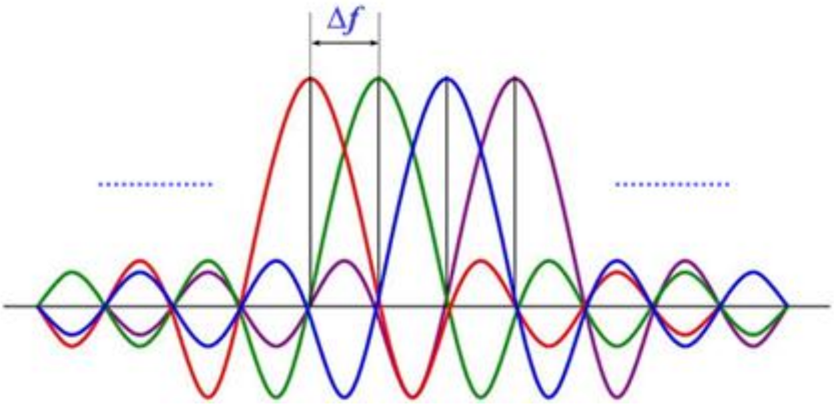


Figure 6.1: OFDM subcarrier spectra

In above figure, sampling instance is an instance at which peak of only one subcarrier exists while all other subcarriers are zero. Δf denotes subcarrier spacing [23].

6.2 PLC-OFDM system

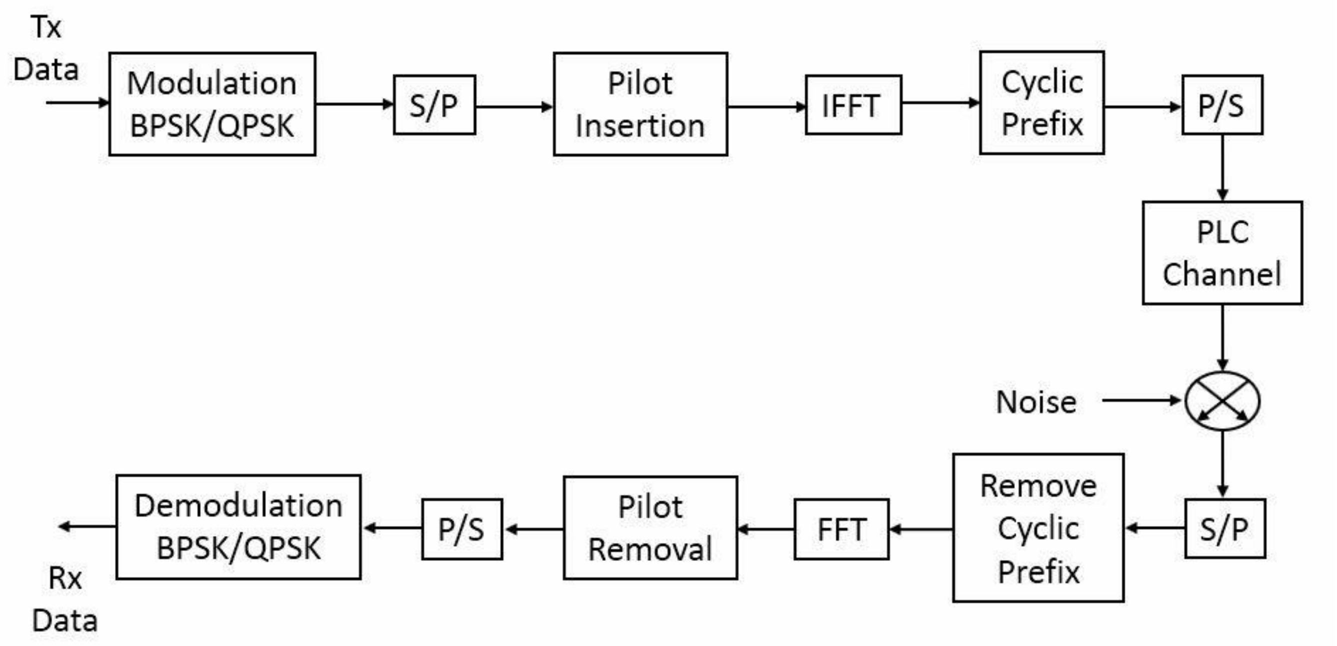


Figure 6.2: PLC-OFDM system

Figure 6.2 shows a standard block diagram of PLC-OFDM system. The system consists of IFFT at transmitter side with its counterpart FFT at receiver end. Pilot symbols and cyclic prefix addition are some of the special features of OFDM system to improve its overall performance. Modulation techniques used may include any PSK technique. Following are the various operational steps carried out in PLC-OFDM transmitter [24]:

1. Modulation

   A serial data at transmitter is initially modulate using Binary Phase Shift Keying (BPSK) or Quadrature Phase Shift Keying (QPSK) or any suitable keying technique. In present thesis, BPSK and QPSK techniques are implemented.

2. Serial-to-Parallel (S/P) converter

   The modulator output is a serial data which should be converted into parallel data streams in order to feed them to IFFT block. Serial-to-Parallel (S/P) converter is implemented to carry out this task.

3. Pilot symbol insertion

   Pilot is a known portion of the signal which is appended to the information signal being transmitted. It is needed for an accurate estimation of the signal at receiver end. The amplitude and phase of the received pilot signal are used to estimate the channel which is used to determine constellation diagram of the received information signal.

4. Inverse Fast Fourier Transform (IFFT)

   The transmitted OFDM signal is mathematically represented as

   $$s(t) = Real\left\{\sum_{n=0}^{N-1} S_n g(t) e^{j2\pi f_n t}\right\} \ldots (6.1)$$

   Equation () shows that it is a Fourier transform where S_n is complex symbol associated with nth subcarrier and g (t) is a pulse shaping function. IFFT exists at transmitter end because a conversion from frequency domain to time domain.

5. Cyclic prefix insertion

   Cyclic prefix is an exact replica of a part of OFDM symbol which is appended at the beginning of OFDM signal. It is needed to maintain the orthogonally of the subcarriers.

6. Parallel-to-Serial (P/S) conversion

   The OFDM signal so obtained is converted back to serial data stream in order to send it through channel.

7. PLC channel and noise

   The channel under consideration is power line channel. The OFDM signal undergoes changes in amplitude and phase of subcarriers due to PLC channel characteristics and noise which adds up in the channel.

8. At the receiver end, all the above mentioned processes are followed in exactly reverse manners. The information signal is recovered at the end.

6.3 Simulation for PLC-OFDM system

To evaluate performance of PLC-OFDM system, a MATLAB simulation was carried out and bit error probability plot was obtained for BPSK-OFDM and QPSK-OFDM systems. Following are the physical parameters which are considered in the simulation.

1. Number of symbols = ns = 10^5
2. Length of FFT = nf = 64
3. Number of subcarriers = nb = 52
4. Number of cyclic prefix bits = nc = 16
5. Total number of bits = 64+16 = 80
6. E_b/N_0 = 0:1:12

The steps followed to simulate the BER plot are:

6.3.1 Transmitter

Step 1: Generating random raw data

t_data → 1 X (nb.ns) matrix → matrix order is 1 X 52e5

Step 2: BPSK/QPSK Modulation

mod_data → 1 X (nb.ns) matrix → matrix order is 1 X 52e5

Step 3: Serial-to-parallel conversion

par_data → ns X nb matrix → matrix order is 10^5 X 52

Step 4: Pilot insertion scheme

[6 zeros …. 1 to 26 data …. 1 zero …. 27 to 52 data …. 5 zeros]

i.e. [**0 0 0 0 0 0** {data symbols from 1 to 26} **0** {data symbols from 27 to 52} **0 0 0 0 0**]

The zeros represent pilot symbols which are known at receiver.

Thus pilot_data → ns X nf → matrix order is 10^5 X 64

Step 5: IFFT_data → ns X nf → matrix order is 10^5 X 64

Step 6: Adding cyclic prefix (16 bits)

[Last 16 bits of IFFT_data (replica) ….. Original IFFT_data]

cyclic_data → matrix order is 10^5 X 64

Step 7: Parallel-to-Serial conversion

ser_data → matrix order is 1 X 80e5

6.3.2 PLC Channel

Step 1: Channel matrix is convolved with transmitter matrix ‘ser_data’

channel_data → matrix order is 1 X 80e5

Step 2: Addition if noise

OFDM has a subcarrier division which enables us to assume that noise level is constant in every subcarrier. So we can consider adaptive white Gaussian noise (AWGN).

noise_data → matrix order is 1 X 80e5

6.3.3 Receiver

Step 1: Serial-to-parallel conversion

Ser_to_para → ns X nb matrix → matrix order is 10^5 X 80

Step 2: Removing cyclic prefix (16 bits)

Neglect first 16 bits as they are the replica of last 16 bits of OFDM signal.

cyclic_rem → matrix order is 10^5 X 64

Step 3: FFT_recdata → ns X nf → matrix order is 10^5 X 64

Step 4: Removing Pilot

rem_pilot → matrix order is 10^5 X 52

Step 5: Parallel-to-Serial conversion

ser_data_1 → matrix order is 1 X 52e5

Step 2: BPSK/QPSK Demodulation

demod_data → 1 X (nb.ns) matrix → matrix order is 1 X 52e5

6.3.4 BER calculation

To obtain the bit error probability plot, information data ‘t_data’ is compared with received data ‘demod_data’. Number of errors those occurred in received data are calculated. Then a ratio is obtained in order to plot BER vs. SNR plot.

$$ratio = \frac{number\ of\ errors}{number\ of\ symbols}$$

The simulation result obtained for PLC-OFDM system with BPSK modulation is as shown in Figure 6.3. Figure 6.4 shows simulation result obtained for PLC-OFDM system with QPSK modulation.

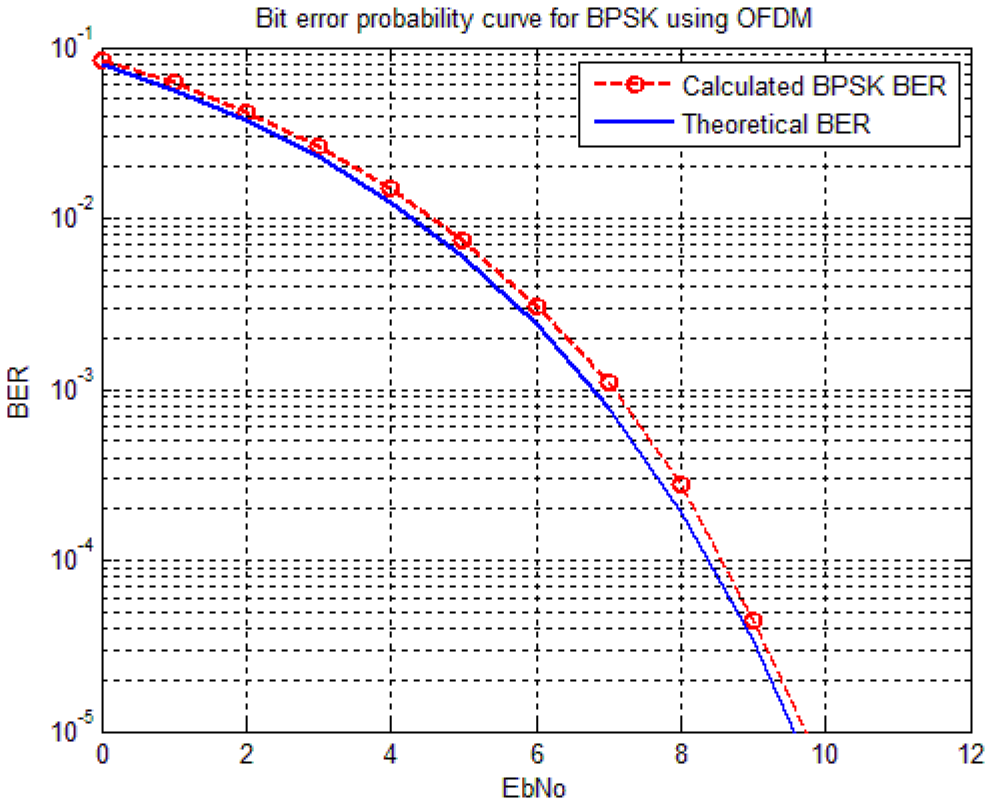


Figure 6.3: PLC-OFDM system with BPSK modulation

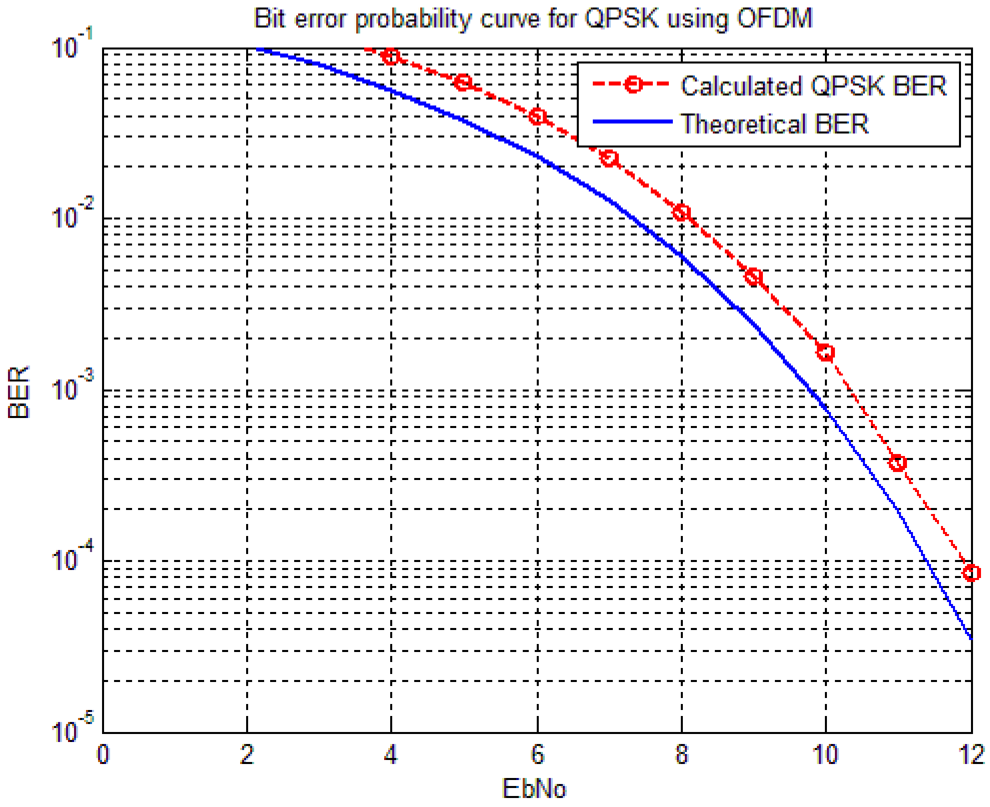


Figure 6.4: PLC-OFDM system with QPSK modulation

CHAPTER 7

CONCLUSION

7

CONCLUSION

7.1 Conclusion

The present thesis is mainly contributed towards the channel modelling of power line channel. An accurate channel model is needed for complete evaluation of any system. Under this context, some of the major points are listed below.

- PLC channel has been modelled by two different approaches and the channel models are compared. A comparison showed that a channel model which considers multipath effects gives better accuracy though it involves complex computations. A channel model based on ABCD parameters is comparatively simple and it involves less computations.
- PLC multipath channel model has been used to create multi-branch channel topology which practically exists. A main focus has been a study of practical scenario of power line networks.
- PLC multipath channel model has been introduced in OFDM based system. A performance has been evaluated in terms of bit error probability.

7.2 Limitation of the present thesis

The present thesis is mainly focused towards power line channel modelling using bottom-up approach. A top-down approach, being less accurate, is not been taken into account which is less complex than bottom-up approach.

The channel model based on multipath bottom-up approach involves very complex computation of channel parameters.

7.3 Future scopes

- A hardware implementation of power line channel can be accomplished which will enable us to obtain measurements of amplitude and phase. The accuracy of channel model proposed may be then tested by comparing simulated and measured values.
- Two approaches discussed in chapter 3 and 4 can be combined to model an approach which will consider multipath effects as well as source and load impedances.
- Performance enhancement algorithms including power minimization algorithm can be implemented to achieve more reliable power line system.
- Fuzzy channel estimation based on multilayer perceptron network may be used at receiver.

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DISSEMINATION

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