PERFORMANCE EVALUATION OF POWER LINE COMMUNICATION CHANNEL AND DESIGN POWER LINE COUPLER CIRCUIT FOR EFFICIENCY IMPROVEMENT

A thesis submitted in partial fulfillment of the requirement for the degree of

Bachelor of Science
in
Electrical Electronic and Communication Engineering

Submitted by

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CERTIFICATION

This thesis paper titled **“Performance Evaluation of Power Line Communication Channel and Design Power Line Coupler Circuit for Efficiency Improvement”** is submitted by the group as mentioned below has been accepted as satisfactory and met the required standard in partial fulfillment of the requirement for the degree of B Sc in Electrical Electronic and Communication Engineering on December 2014.

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DECLARATION

It is hereby declared that the work presented in the thesis titled **"Performance Evaluation of Power Line Communication Channel and Design Power Line Coupler Circuit for Efficiency Improvement"** is an outcome of the study carried out by the author under the supervision of Capt. M. Mahbubur Rahman. It is also declared that neither of this thesis paper nor any part therefore has been submitted anywhere else for the award of any degree, diploma or other qualifications.

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Table of Contents

LIST OF FIGURES

LIST OF ABBREVIATION

PLC	-	Power Line Communication
NB-PLC	-	Narrow Band Power Line Communication
BB-PLC	-	Broad Band Power Line Communication
OFDM	-	Orthogonal Frequency Division Multiplexing
ASK	-	Amplitude Shift Keying
FSK	-	Frequency Shift Keying
PSK	-	Phase Shift Keying
LAN	-	Local Area Network
MOV	-	Metal Oxide Varistor
HV	-	High Voltage
MV	-	Medium Voltage
HDDTV	-	High Definition Digital Television
IEEE	-	Institute of Electrical and Electronics Engineers
CSMA	-	Carrier Sense Multiple Access
CA	-	Collision Avoidance
I.I.D	-	Independent and Identically Distributed
BCH	-	Bose-Chaudhuri Hocquenghem
FEC	-	Forward Error Correction
AM	-	Amplitude Modulation
QAM	-	Quadrature Amplitude Modulation
SNR	-	Signal to Noise Ratio
MA	-	Margin Adaptive
RA	-	Rate Adaptive
BER	-	Bit Error Rate

DFT	-	Discrete Fourier Transform
ISI	-	Inter Symbol Interference
DAB	-	Digital Audio Broadcasting,
DVB	-	Digital Video Broadcasting,
ADSL	-	Asymmetric Digital Subscriber Line
SST	-	Spread Spectrum Technique
PSD	-	Power Spectral Density
DSSS	-	Direct Sequence Spread Spectrum
CDMA	-	Code Division multiple Access
FD	-	Frequency Domain
TD	-	Time Domain
IAT	-	Inter Arrival Time
WGN	-	White Gaussian Noise
EMI	-	Electro Magnetic Interference
EMC	-	Electro Magnetic Compatibility
MF	-	Medium Frequency
RF	-	Radio Frequency

Chapter 1: Introduction

1.1 Introduction

Power line communication is a fairly recent technology. "Power Line Communications" generally means any technology which enables data transfer at narrow (NB) or broad band (BB) speeds through power lines using advanced modulation technology. It is an approach to utilize the currently existing power lines for the transmission of information data. Currently every house and building has properly installed electricity lines. By using the already existing AC power lines as a medium to transfer the information data, it becomes very easy to connect the houses with a high speed network access point without installing new wirings and structures.

A Power Line Communication System is a system where communication signals are sent and received on household and industrial 50Hz current-carrying power line. Power Line Carrier Communication (PLC) has recently become a popular technology for automation of home and networking. It's because power line is a relatively cheaper and more robust communication channel used all around the world except wireless channel. It is used more commonly used than any other communication channel. A simple digital communication system generally consists of an encoder and a modulator on the transmission side, and a decoder and a demodulator on the receiving side. However, in order to support two ways communication (full duplex or half duplex), modem (modulator/demodulator) devices are designed and used in communication systems nowadays. A power line modem is an all-in-one device consists of an encoder, a decoder, a modulator, and a demodulator. As the current carrying AC mains power line is used as a transmission medium, extra coupling circuits are required in power line modems for better protection, isolation and impedance matching. Power line modems are used in various applications. However, this report will cover an overall analysis of establishing an analytical model of a power line communication system and verification of transit-receive capability. The development of PLC systems for broadband multimedia applications requires a vast knowledge of the channel characteristics and the main subject of focus that may influence the communication over this channel. PLC has the potential and possibility of becoming the preferred connectivity solution to homes and offices. Additionally, indoor power line networks can serve as local area networks (LAN) offering high-speed data, audio, video and multimedia applications. PLC technology eliminates the need for new wires by using already-existing infrastructure which is much more prevalent than any other wired system.

Power line networks, however, offers a hostile channel for communication signals, as their basic purpose is the transmission of electric power at low frequencies (50 Hz or 60 Hz). Noise, multipath, selective fading and attenuation are major properties of power line grids and they must be considered when designing a PLC systems. Additionally, random impulsive noise characterized with short durations and very high amplitudes is identified as one of the major deficiencies that worsen the performance of PLC systems.

Orthogonal frequency division multiplexing (OFDM) is the widely used modulation technique for PLC and has been regarded as the modulation scheme for broadband PLC and is used as the modulation scheme in this work. It's because OFDM reduces the effects of multipath and provides high robustness against selective fading. It is also effective in impulsive noise environments and performs better than single-carrier modulation techniques. If an OFDM symbol is affected by impulsive noise, the effect is spread over multiple subcarriers due to the discrete Fourier transform (DFT) at the receiver. Consequently, each of the simultaneously transmitted communication symbols are only affected by a fraction of the occurring impulsive noise.

To achieve reliable outcomes, suitable channels and noise models are used in the investigations. In this thesis, it will also be discussed the power line channel transfer function .This section will also discuss several noise mitigation techniques and also means of negating multipath fading and multipath propagation. The actual noise scenario in power networks can be represented by classifying the noise into two main classes: Background noise and Impulsive noise. Background noise is modeled as an (Additive White Gaussian Noise) AWGN whereas impulsive noise is modeled using a Poisson-Gaussian process. The performance of PLC is tested under three different impulsive noise scenarios that are based on practical measurements. Results show that impulsive noise can have a severe effect in the bit-error rate of OFDM-based PLC systems.

To reduce the effect of impulsive noise, conventional time domain nonlinearities are examined in this thesis under PLC environments. The threshold selection problem is studied and an adaptive-threshold selection method based on minimum bit-error rate (BER) is proposed as a solution to this problem. At the cost of additional complexity, the effect of impulsive noise is further mitigated using a novel joint time-domain/frequency-domain suppression technique. This technique uses a time-domain clip/blank nonlinearity jointly with a frequency-domain noise suppression technique found in the literature.

Channel coding is essential for most telecommunication systems .Convolutional codes in a practically-proven PLC channel impaired with AWGN and impulsive noise will also be described briefly. Random interleaving is used to prevent the bursty nature of the impulsive noise present in PLC channels. Results show considerable performance gains especially in heavily-disturbed environments, where signal-to-noise ratio (SNR) gains of more than 15 dB can be achieved with a code rate of 1/3. Bit-interleaved convolutionally coded OFDM completely eliminates effect of impulsive noise in weakly disturbed noise environments, while a negligible effect may remain in medium disturbed environments.

The adaptability feature of OFDM can be exploited by using adaptive modulation methods leading to significant improvements in the system's performance, efficiency and robustness. In later chapters of this dissertation, bit/power loading algorithms are investigated. A new power-loading algorithm that minimizes the transmission power for target BER and data rate constraints is introduced.

Results indicate that, in a PLC channel impaired with impulsive noise, the algorithm achieves performance gains of more than 4 dB SNR over conventional OFDM systems. Furthermore, a novel minimum-complexity bit-loading algorithm that maximizes the data rate given BER and power level constraints is proposed in chapter 6. Results show that this bit-loading algorithm achieves almost identical performance as the incremental algorithm but with much lower complexity. The performance of both algorithms is tested under PLC channels against well-known loading methods and their superior performance is proved.

1.2 Brief History of Power Line Communication

The previous history of PLC is introduced in 1999. According to Brown, idea of using power-lines for communication signal is old. In 1838, Edward Davy proposed remote electricity supply metering in order to check the voltage levels of batteries at unmanned sites in the London–Liverpool telegraph system. In 1897, Joseph Routin and C.E.L. Brown patented their power-line signaling electricity meter in Great Britain. Chester Thoradson from Chicago patented his method of remote reading of electricity meters in 1905. Thoradson's system used an additional wire for sending signal, but unfortunately it was not taken into use because the commercial benefits of the system were insufficient. Power line communication has been a topic if interest for quite some time, but only the Narrow band tele-remote relay applications, public lighting and home automation has been commonly used. Use of Broadband over PLC only started at the end of the 1990s:

In 1950, PLC method was attempted at a frequency of 10Hz, 10kW of power, one-way relay remote control for town lighting.

In Mid 1980s research for using the electrical Grid to support data transmission began on bands between 5 - 500 KHz, always in a one-way direction.

In 1997 occurred the first tests for bidirectional data signal transmission over the electrical supply network and the beginning of research by Ascom (Switzerland) and Norweb (U.K.)

In 2000 first tests were carried out in France by EDF R&D and Ascom.

1.3 Components of PLC

Basically a PLC system contains the following –

1. A modulator for data transmission.
2. Coupler circuits at both transmission and receiving end for coupling and decoupling data signal in and from power line.
3. A demodulator for receiving data signal.
4. Line trap circuits for impedance matching.

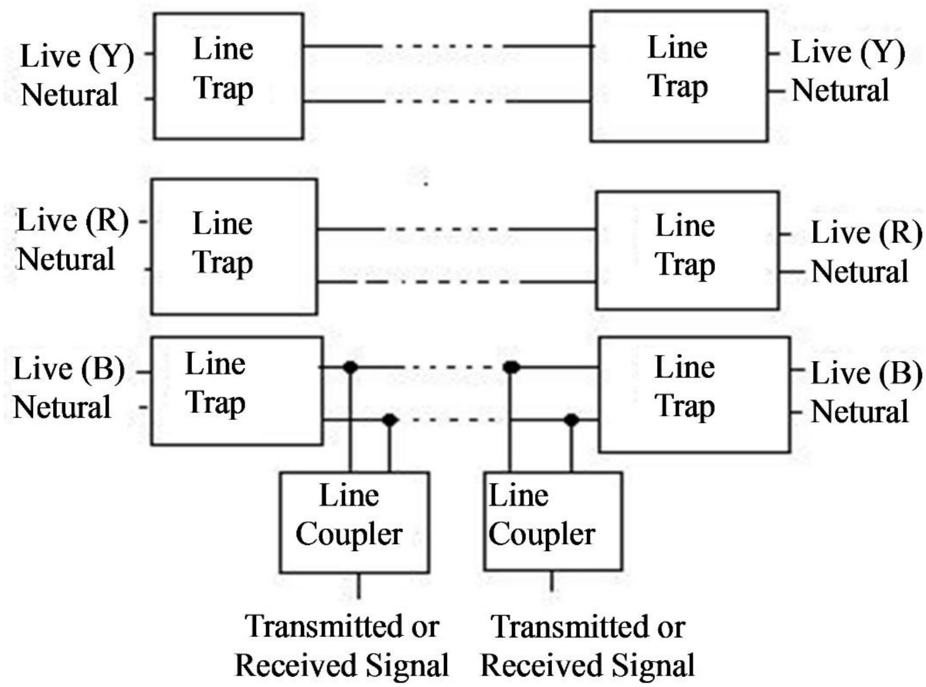

Fig 1.1: Block diagram of a PLC with line traps

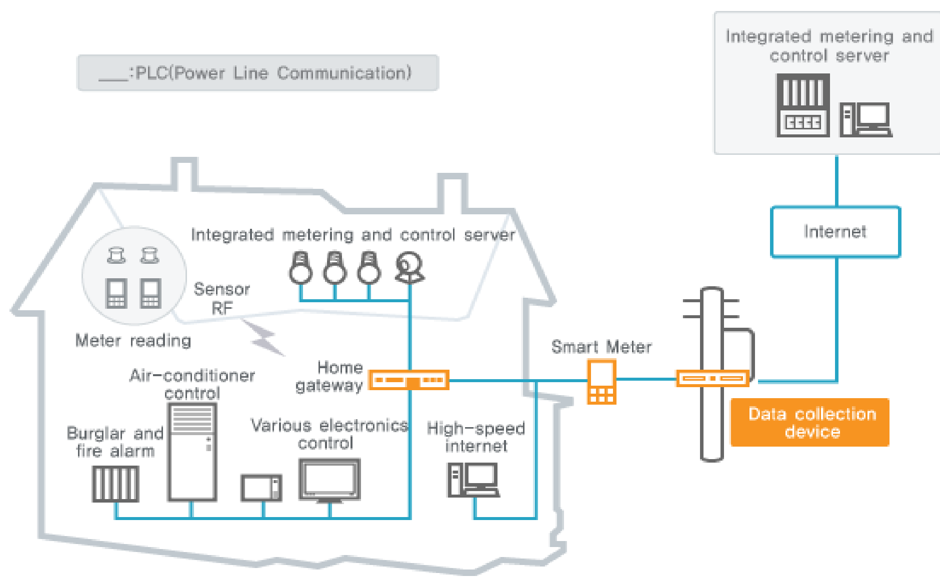

Fig 1.2: A simple PLC model

The basic Components to make a simple PLC circuit are –

- PCB and Breadboards.
- Resistors.
- Capacitors.
- Inductors.
- Power resistors (for power supply).
- Zener Diode.
- Voltage Regulators.
- Transistors.
- DC sources.
- AC power plugs.
- High quality isolators for protection.
- Communication port cable and connectors.
- Indicator Lights.
- Casing for module.
- Others

1.4 Data Transmission through PLC

Generally Power line communication technology enables data transfer at narrow (NB) or broad band (BB) speeds. Narrowband PLC works at lower frequencies (3-500 kHz), lower data rates (up to 100s of kbps), and has longer range (up to several kilometers), which can be extended using repeaters. Broadband PLC works at higher frequencies (1.8-250 MHz), high data rates (up to 100s of Mbps) and is used in shorter-range applications.

1.4.1 Narrow-Band PLC

Recently, narrowband Power Line Communication has been receiving widespread attention due to its applications in the Smart Grid. Another application that narrowband PLC has been used in is smart energy generation, particularly in micro-inverters for solar panels.

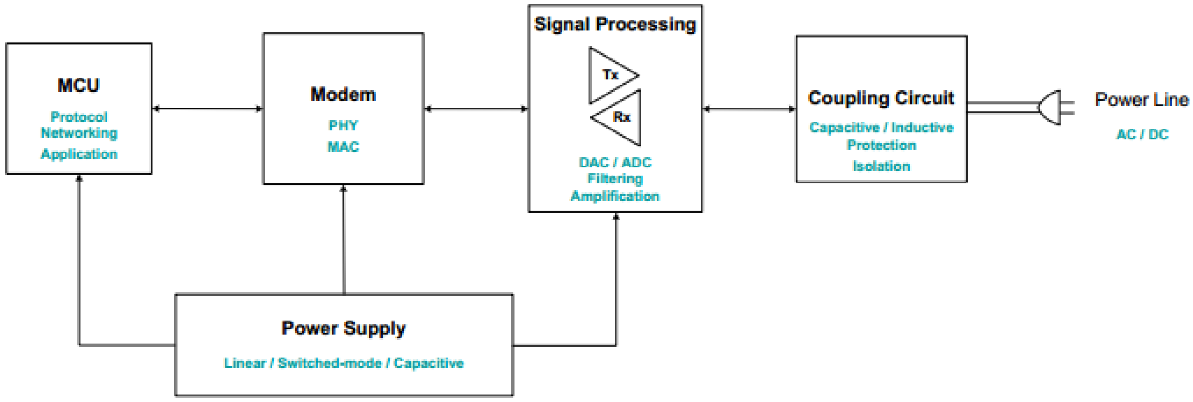

Fig 1.3: Block Diagram of a NB-PLC

NB-PLC finds applications wherever there is electrical wiring, from utility power grid and distributed renewable energy systems to homes and buildings, public lighting, and plug-in electric vehicles. There is also a large variety of custom applications involving AC, DC or un-powered lines, like fireworks control, emergency lighting, dive data management, submersible water pumps – to mention just a few. Each implementation has its own challenges that mainly depend on the channel characteristics and market requirements.

1.4.2 Broad-Band PLC

Broad-band PLC, basically has been accepted as a last-mile solution for Internet distribution and home networking. With its high data rates and no additional wiring, broadband PLC is considered as an effective and attractive technology for multimedia distribution within homes and offices. This can be easily seen by the recent acquisitions of Intellon by Atheros, Coppergate by Sigma, DS2 by Marvell, and Gigle by Broadcom, all in the Home Area Networking (HAN) segment.

Broadband PLC allows moderately high-speed digital data transmission over the public Electric power distribution line. Broadband Power Line uses higher frequencies, a wider frequency range and slightly different technologies from other methods of power-line communications to provide high-rate communication over longer distances. Broadband Power Line uses frequencies which are part of the radio spectrum allocated to over-the-air communication services therefore the prevention of interference to, and from, these services is a very important factor in designing BPL systems.

At first it was hoped that BPL would allow electric companies to provide high-speed access to the Internet across what providers call "the last mile." In this scenario, the service provider would deliver phone, television and Internet services over fiber or copper-based long haul networks all the way to the neighborhood or curb and then power lines would bring the signals into the subscriber's home. The BPL subscriber would install a modem that plugs into an ordinary wall outlet and pay a subscription fee similar to those paid for other types of Internet service. No phone, cable service or satellite connection would be required.

However it is evident that even if BPL is not accepted as a viable way to deliver high-speed Internet access, it may find a place in helping consumers to manage their energy consumption. High-speed data transmission between electrical plugs in a building would allow devices such as thermostats, appliances and smart meters to communicate with each other.

1.5 Advantage and Necessity of PLC

The Main Advantages of PLC are-

- Use of the existing electrical network, which involves potentially covering the entire country under consideration.
- Quick deployment.
- Both communication and power transfer can be possible on the same circuit.
- No additional wiring.
- Power lines have higher mechanical strength over normal communication lines.
- Lower attenuation over long distance.
- Implementation cost is reduced.
- A robust encryption method.
- Power lines usually provide the shortest routes between power stations.

The key advantage of PLC is the use of existing electrical lines as communication medium, which provides the major benefit of eliminating considerable costs of installing networking infrastructure, like dedicated cables or antennas.

Data is sent on the power lines by superposing a modulated high-frequency carrier signal on the line voltage, being high, medium or low, AC or DC. The carrier signal is then de-coupled and demodulated at the receiving end to recover the information.

PLC is widely used in the Smart Grid and in micro-inverters. As the market gets familiar with this technology, PLC should see wider adoption in other applications like lighting (e.g. traffic light control, LED dimming), industrial (e.g. UPS communicating to a network device, irrigation control), machine-to-machine (e.g. vending machines, a hotel's reception-to-room communication), telemetry (e.g. offshore oil rigs), transport (e.g. Electronics in cars, trains and airplanes) and indeed, applications of PLC are only limited by one's creativity. This thesis paper will provide a little more about PLC in energy generation and conservation markets.

1.6 Limitations of PLC

- Noise.
- Signal attenuation.
- Fading.
- Multipath propagation.
- Difficult to incorporate over long distance.
- Time delay in sending signals.
- Complex forms of communication is not possible.
- Regulatory and standardization issues.

The most recent controversy around power line relates to the interference that it causes for other electrical equipment as power line signals radiate into the air so have a tendency to interfere with other electrical devices like short wave and medium wave radios that share the same frequency which can interfere with the functioning of these devices.

The limitations and disadvantages have been briefly described in chapter 2 (Barriers of communications in PLC).

1.7 Literature review

Power line communication (PLC) offers a convenient and inexpensive medium for data transmission, however this technology still face a difficult challenge: the channel modeling. Although enormous effort has been devoted to determining accurate channel models for the power line, so far, there is not a widely accepted model in the PLC community. The discussion is focused on the modeling Power line communication system and verification of transit-receive capability.

The basic principle of power line communications (PLC) is to use the existing electrical power line structures for telecommunication purposes. Over the years, power line networks have served as a medium of transmission and distribution of electricity signals. Until recently, communication over power lines was restricted to low-speed functions such as remote metering and operations management that serve the needs of power supply utilities. This limited scope of power line functions changed recently, on account of the ever increasing demand for high-speed broadband multimedia communications.

Power Line Communication (PLC) is also called power-line carrier communication (PLCC). PLC uses electric power lines to carry information over the power line. It is a technique used in home automation for remote control as it can use the household electrical power wiring as a transmission medium. PLC has been a very important interdisciplinary topic for power, communications, industrial, and automation engineers and researchers since the 1980s. PLC promises to be an enabling home network technology due to its ability to deliver data over existing power lines in homes. Similar to RF, the power line is a shared medium that exists in a noisy environment, although the respective noise sources differ markedly.

Motors, switch-mode power supplies, fluorescent ballasts, and other impairments, which generate substantial impulse and wideband noise share power lines.

Recently, with the explosive growth of the Internet and telecom technology home automation experience an accelerating growth based on different kinds of residential network. At the present there are several kinds of transmission medium in residential network, such as coaxial-cable, radio, microwave, millimeter wave, power line and fiber optics. Compared with other kinds of transmission medium, power line has distinct advantage in setting up a network without additional line installation and existing digital devices, including home appliances and information devices, at a very low cost.

Many applications are operating at high speed and a fixed connection is often preferred. If the power utilities could supply communication over the power line to the customers it could make a tremendous breakthrough in communication.

Every household would be connected at any time and services being provided at real time. Using the power line as a communication medium could also be a cost effective way compared to other system because it uses an existing infrastructure, wire exists to every household connected to the power line network. On the other hand, device power in home automation still can be supplied by power line itself. So PLC rapidly becomes a popular solution to set up residential network.

Concerning this cases, an attempt is taken to establish a proper analytical model of a Power Line Communication model and performed several experiments to verify it transit-receive capability.

In case of home electrical line, Signal strength or signal attenuation is crucial in order to design home automation communications circuits. PLC communication signals via main power lines are transmitted from a part of the home and received at the other side.

In this thesis an attempt to come up with an effective model of PLC system is taken and focused on verification of transit-receive capability of the system.

While doing so the points below are kept on focus –

- Making the circuit as simple as possible.
- Mitigating the cost.
- Analyzing and changing the circuit parameters for different frequencies and different AC levels.
- Using the existing equipment available in markets of Bangladesh.
- Improving the efficiency.
- Reducing the noise effect as much as possible.
- Opening new scopes for research

1.8 Previous works on PLC

Many researches on PLC have been done before and still being done such as,

- PLC Channel-Modeling.
- Design and Standardization of Models.
- Smart metering.
- Automotive applications.
- Effect of noise and mitigation of noise on PLC.
- Performance of PLC
- Modulation schemes for PLC.
- MIMO (Multiple input multiple output) PLC etc.

PLC is a timely demanding research topic and more and more researches are undergoing regarding this topic.

1.9 Organization of this thesis work

This thesis is comprised of four chapters. The first chapter serves as an introduction to the thesis whereas the second chapter presents an analytical survey of the field of power line communications and related topics.

Chapter three focuses on the practical implementation of PLC model. The details of the PLC project have been put up on several circuits. This chapter will provide circuit details, component details as well as the operation and implementation a number of designed circuit. Chapter four includes the result and discussion. The summary of the main conclusions of this dissertation and presented possible future directions will be discussed in this chapter.

Chapter 2: Analysis of power line

2.1 Mathematical model of PLC

This chapter will cover the mathematical models of PLC including transfer function equations, noise models, attenuation, impedance matching as well as mitigating various barriers in power line communication.

2.1.1 Channel Model Analysis

In Power line transmission the propagation of data signals do not follow single path or uni-path, but they follow a multipath following a pattern very similar to wireless signals involved in cellular transmission.

Multipath propagation is also responsible for delay (τ_i) in PLC, which is given by:

$$\tau_i = \frac{d_i\sqrt{\varepsilon_r}}{c_0} = \frac{d_i}{v_p} \quad (1)$$

d_i is the length of path, c_0 is speed of light and $\sqrt{\varepsilon_r}$ is dielectric constant of insulating material.

The power line transfer function having multipath propagation is given by,

$$H(f) = \sum_{i=1}^{N} g_i \,.\, A(f, d_i).\, e_i^{-j2\pi f\tau_i} \quad (2)$$

$H(f)$ is frequency response of channel between two points. When the grid network grows big and complex it could be separated into sub-channels for individual study. A (f,d_i) are cable losses which could be in the form of heat or signal leakage etc. f is the frequency of operation, g_i is weight factor which is directly proportional to number of reflections and path followed:

$$|g_i| \leq 1 \quad (3)$$

The values of g_i and A (f,d_i) are determined experimentally. Based upon above given factors a mathematical model of multipath PLC.

$$H(f) = \sum_{i=1}^{N} g_i \,.\, A(f, d_i).\, e_i^{-j2\pi f\tau_i} \quad (4)$$

Based upon extensive investigation on experimental data A (f, d_i) can be approximated by the mathematical formula for attenuation factor (α)

$$\alpha(f) = \alpha_0 + \alpha_1 . f^k \tag{5}$$

α_0 and α_1 are attenuation parameters leading to:

$$A\,(f\,, d) = e^{-\alpha(f).d} = e^{-(\alpha_0+\alpha_1.f^k).d} \tag{6}$$

Using A (f, di) in $H\,(f)$ gives the channel model for PLC transmission line:

$$H(f) = \sum_{i=1}^{N} g_i \,.\, e^{-(\alpha_0+\alpha_1.f^k).d} .\, e_i^{-j2\pi f(d_i/v_p)} \tag{7}$$

g_i = weighting factor

$e^{-(\alpha_0+\alpha_1.f^k).d}$ = Attenuation portion

$e_i^{-j2\pi f(d_i/v_p)}$ = Delay portion

2.1.2 Noise Analysis

Background noise is considered to be Additive White Gaussian Noise (AWGN) W_k for PLC analysis. The impulsive noise is given by:

$$i_k = b_k * g_k \tag{8}$$

Where, b_k is the Poisson process which is the arrival of the impulsive noise, g_k is the white Gaussian process with mean zero and variance $2\sigma^2$. That is Gaussian noise of magnitude varying up to 35 dB and is distributed among data bits complying Poisson distribution. b_k is the probability of getting hit by noise and g_k is the random variable denoting the varying amplitude of noise. The total noise n_k is given by:

$$n_k = W_k + i_k \tag{9}$$

$$n_k = W_k + b_k * g_k \tag{10}$$

Arrival of the impulsive noise follows the Poisson process with a rate of R units per second, so that the event of k arrivals in t seconds has the probability distribution as:

$$p_k(t) = e^{-\lambda t}(-\lambda t)^k/k! \tag{11}$$

Here, $p_k =$ Probability distribution

$\lambda =$ wavelength

$k =$ No. of arrivals

$t =$ time duration

Let a_k be the received signal, and then the transmitted signal r_k is given by:

$$r_k = a_k + n_k \tag{12}$$

In case if the modulation technique used is OFDM with BPSK as bit modulation, received signal could be characterized with the expression;

$$\mathrm{r_k} = \frac{1}{\sqrt{\mathrm{M}}} \sum_{\mathrm{m}=0}^{\mathrm{M}-1} \mathrm{a_m} \mathrm{e}^{\frac{\mathrm{j}2\pi\mathrm{mk}}{\mathrm{M}}} + \mathrm{W_k} + \mathrm{i_k} \tag{13}$$

$$\text{Where } \mathrm{k} = 0,1,2,3 \ldots\ldots, \mathrm{M}-1$$

Here, M is number of sub channels/subcarriers and a_m is (+1,-1) BPSK symbol.

This section discussed mathematical model of noise characteristics involved in PLC.

2.2 Transfer function of a Power Line

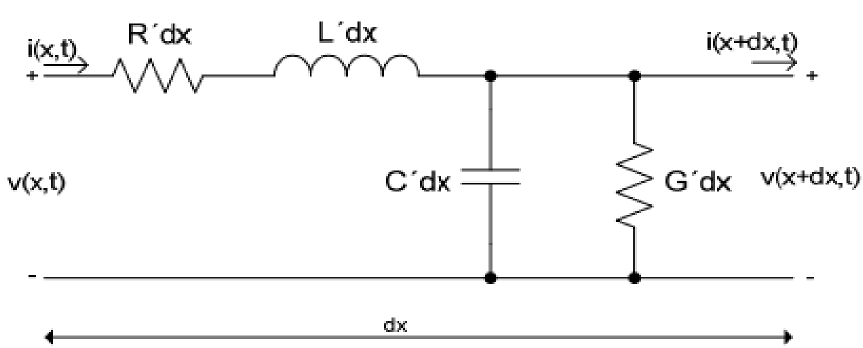

Fig 2.1: Elementary cell of a transmission line

The time dependent telegrapher's equations which are for the elementary line transmission cell, shown in Fig. 2.1, the following:

$$\frac{\partial v(x,t)}{\partial x} + R' i(x,t) + L' \frac{\partial i(x,t)}{\partial t} = 0 \quad (14)$$

$$\frac{\partial v(x,t)}{\partial x} + G' v(x,t) + C' \frac{\partial i(x,t)}{\partial t} = 0 \quad (15)$$

In these equations x denotes the longitudinal direction of the line and R', L', G' and C' are the per unit length resistance (Ω/m), inductance (H/m), conductance (S/m) and capacitance (F/m) respectively. The electric quantities are dependent on the geometric and constitutive parameters.

The parameters to describe a transmission line are the characteristic impedance Z_c and the propagation constant γ:

$$Z_c = \sqrt{\frac{R' + j\omega L'}{G' + j\omega C'}} \quad (16)$$

$$\gamma = \alpha + j\beta = \sqrt{(R' + j\omega L')(G' + j\omega C')} \quad (17)$$

The power line model is considered as a black box described by transfer function, the method for modeling the transfer function of a power line channel uses the chain parameter matrices describing the relation between input and output voltage and current of two-port network.

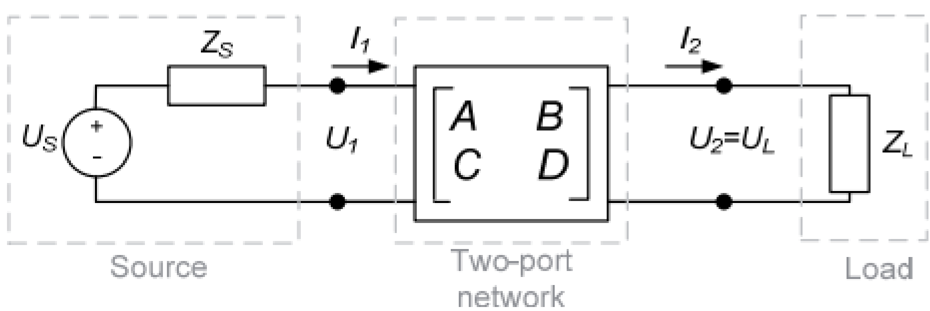

Fig 2.2: Two-port network connected to a source and load

The relation between input voltage and current and output voltage and current of a two port network can be represented as:

$$\begin{bmatrix} U_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} U_2 \\ I_2 \end{bmatrix} \tag{18}$$

The transfer function of two-port network is given by the equation:

$$H = \frac{U_L}{U_S} = \frac{Z_C}{AZ_C + B + CZ_C Z_S + DZ_S} \tag{19}$$

The ABCD matrix for the transmission line with characteristic impedance Z_c, propagation constant γ and length l can be calculated as

$$\begin{bmatrix} U_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} \cosh(\gamma l) & Z_C \sinh(\gamma l) \\ \frac{1}{Z_C} \sinh(\gamma l) & \cosh(\gamma l) \end{bmatrix} \begin{bmatrix} U_2 \\ I_2 \end{bmatrix} \tag{20}$$

2.3 Barriers of communication in PLC

The main barriers of PLC are –

- Noise
- Attenuation
- Fading
- Multi-path propagation

2.3.1 Noise

When the PLC signals are severely attenuated, the noise becomes a significant concern for data reception.

Generally, channel noise is generated by electrical loads and varies with time of day, location and frequency. The noise power level at a certain location is the sum of noise waveforms from different sources and depends on the distance to noise sources. Also, noise has greater power in the lower frequency range and decreases at higher frequency.

As one would expect, there are many sources of noise on the power lines. They can be classified in several classes.

A detailed classification of the power line noise is listed as follows:

- Colored Background Noise: Appliances and components operating at low power, collectively generates noise with relatively low power spectral density (PSD).

- Narrow band noise, mostly amplitude modulated sinusoidal signals caused by ingress of radio broadcasting stations.

- Periodic impulsive noise asynchronous to the main frequency, which is mostly caused by switched-mode power supplies.

- Periodic impulsive noise synchronous to the mains frequency, components like rectifier diodes, transistors whose cut off voltage and threshold voltage leads to switching actions in synchronous to frequency of mains power.

- Asynchronous impulsive noise, which is caused by switching transients in the power network.

Collective noise is the sum of all the noise types mentioned above. Colored Background Noise and Narrow Band Noise are considered as background noise which uniformly spread throughout the spectrum, as their rate of change of magnitude is very slow. On the contrary, the last three are termed as impulsive noise since their amplitude changes rapidly.

Background noise is considered to be Additive White Gaussian Noise (AWGN)

An important feature of electric networks, particularly in the "last mile" area and in-building wiring, is the susceptibility to a variety of signals. In order to use power lines for reliable high-speed PLC data transmission, it is vital to study and understand the different interference scenarios that exist in the electric network. Interference in power lines usually originates from electrical devices connected to the network or in its proximity. Interference can occur due to the normal operation of some electrical machinery and devices. In addition, switching electrical appliances (on and off) causes impulsive current and voltage peaks propagating along the electrical wiring. Typical noise-generating electrical devices include light dimmers, fluorescent and halogen lamps, universal motors and so forth.

Another kind of interference affecting broadband power line communications (BPL) is related to electromagnetic interference (EMI) and electromagnetic compatibility (EMC) of power lines.

Electric wiring is vulnerable to irradiation from radio services operating in the same radio frequency (RF) band. BPL devices typically use the frequency band (2 − 30 MHz).

An example of radio services occupying frequencies within this band is the amateur radio that has been using portions of the medium-frequency (MF)

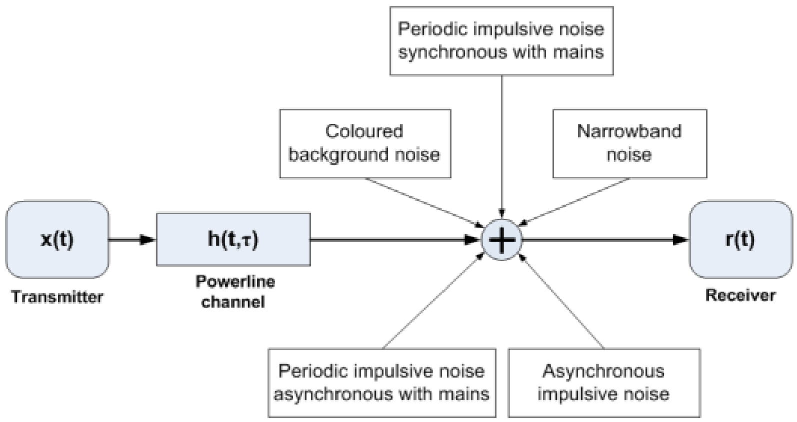

Fig 2.3: Noise scenario in power line channel

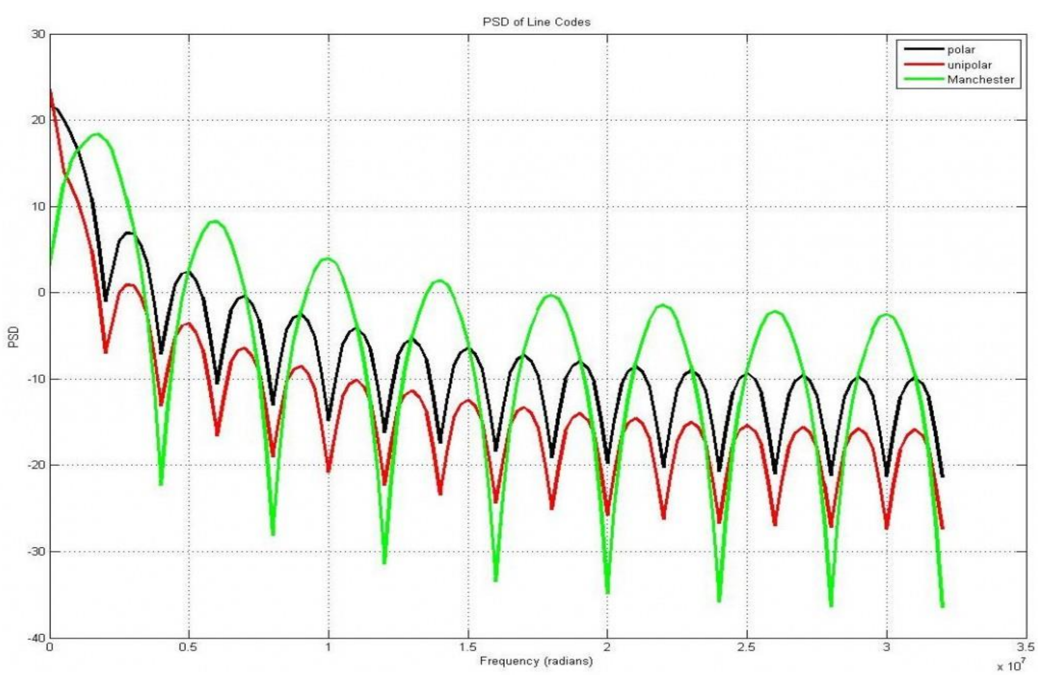

Fig 2.4: PSD of line codes

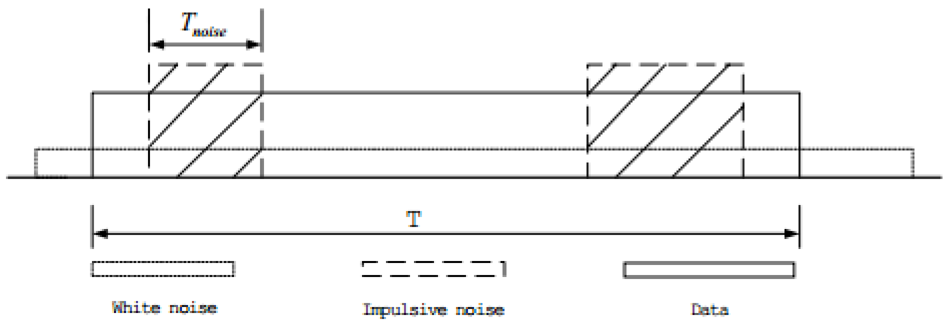

Fig 2.5: Impulsive and White Gaussian noise in a time unit

2.3.2 Attenuation

The communication signal is attenuated with distance. The relative efficiency of power- and carrier-frequency transmission also differs significantly. Many factors are involved in the carrier signal losses on a transmission line. The primary factors are: carrier frequency, line construction, phase conductor size and material, shield wire size and material, type and location of transpositions, weather conditions, earth conductivity, and insulator leakage. Line losses will increase as the frequency goes higher. This is primarily because of the fact that most losses are due to shunt capacitance which becomes a lower impedance at higher frequencies. Conductor losses also play a role in increasing attenuation, due to the increased skin effect which means that less conductor area is available to higher frequency current.

Attenuation measurements are made using the hardware layout shown in figure below

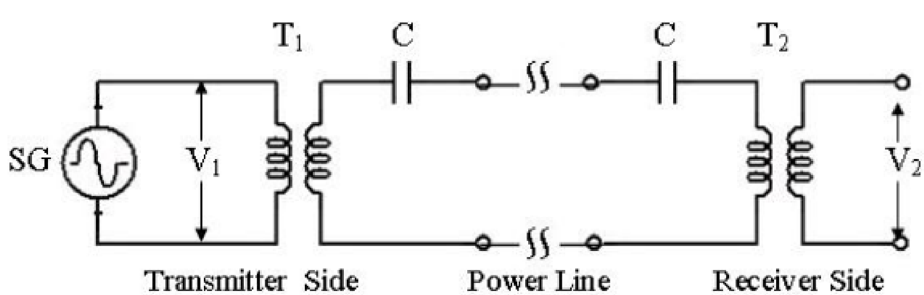

Fig 2.6: Test circuit of the power line attenuation measurements

Attenuation differs in different areas, a study of attenuation in power lines for rural, urban and industrial area are shown in the following figure (Fig 2.7)

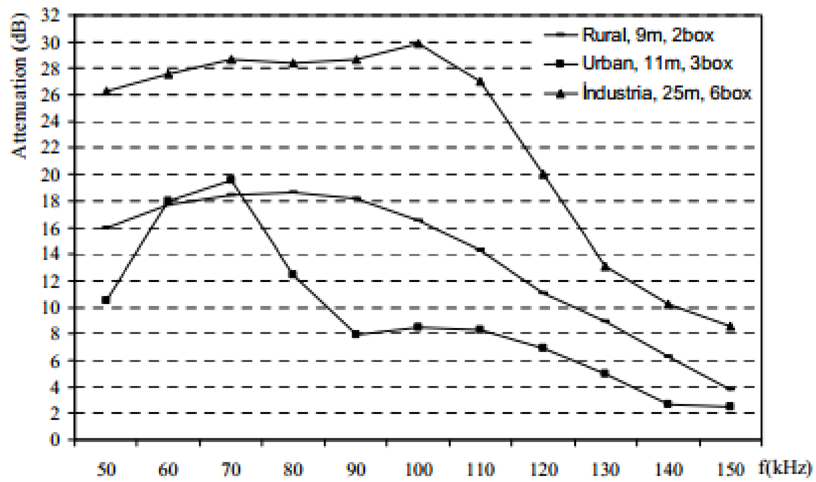

Fig 2.7: power line attenuation for rural, urban and industrial area

2.3.3 Fading effect on PLC

Even though power line communications is an attractive alternative for broadband Internet access for the last mile and in-home/office networking, many difficulties and challenges exist.

The characteristics of the power line that need to be contended with are time-varying frequency dependent channel attenuation of up to 60 dB, reflections from non-terminated points resulting in multipath fading, and various types of noise . When a signal arrives at an impedance discontinuity, it will be partially or wholly reflected depending on the impedance. The transmitted part will proceed further to the receiving end. The reflected signal moves in the opposite direction and again undergoes division into reflected and transmitted components when it faces another discontinuity. Fading in PLs occur due to multiple reflections of the signal at the interconnections and impedance mismatches of the network and loads. Depending on the signal power, the nature of the loads and discontinuities encountered in the signal path, there is variation in the distribution of the received signal envelope. For a single noise source, if the phases of the individual reflected waves are random, but the time delays are approximately equal for all the waves then the received envelope is Rayleigh distributed. But if the received signal has a strong dominant component corrupted by additive narrowband Gaussian noise, then the distribution can be considered as Rician. In general as the background noise is the result of summation of various noise sources, the received signal can be considered as multipath scattering with relatively larger time delay spread between different clusters. The distribution within a cluster is Rayleigh distributed, but as a whole the received envelope is Nakagami-m distributed.

2.3.4 Multipath propagation in a PLC

Signal propagation does not only take place along a direct line-of-sight path between transmitter and receiver, but additional paths (echoes) must also be considered. The result is a multipath scenario with frequency selective fading. Multipath signal propagation is studied by a simple example which can be easily analyzed.

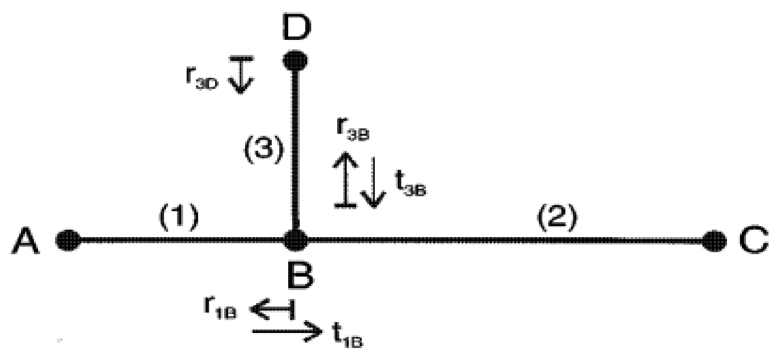

Fig 2.8: Multipath signal propagation

A and C are assumed to be matched, which means $Z_A = Z_{L1}$ and $Z_C = Z_{L2}$. The remaining points for reflections are B and D, with the reflection factors denoted as r_{1B}, r_{3D}, r_{3B} and the transmission factors denoted as t_{1B}, t_{3B}. With these assumptions, an infinite number of propagation paths is possible in principle, due to multiple reflections (i.e. A→B→C, A→B→D→B→C, and so on). Each path has a weighting factor g_i, representing the product of the reflection and transmission factors along the path. All reflection and transmission factors at power lines are basically less or equal to one. This is due to the fact that transmission occurs only at joints, where the load of a parallel connection of two or more cables leads to resulting impedance being lower than the characteristic impedance of the feeding cable. Hence, the weighting factor g_i a product of transmission and reflection factors is also less or equal to one, i.e.

$$|g_i| \leq 1 \tag{21}$$

The more transitions and reflections occur along a path, the smaller the weighting factor gi will be. Furthermore, longer paths exhibit higher attenuation, so that they contribute less to the overall signal at the receiving point. Due to these facts, it is reasonable to approximate the basically infinite number of paths by only N dominant paths, and to make N as small as possible.

The delay τ_i of a path

$$\tau_i = \frac{d_i\sqrt{\varepsilon_r}}{c_0} = \frac{d_i}{v_p} \tag{22}$$

With length and frequency. The signal components of the individual paths have to be combined by superposition. Therefore, the frequency response from A to C can be expressed as

$$H(f) = \sum_{i=1}^{N} g_i \,.\, A(f, d_i).\, e_i^{-j2\pi f \tau_i} \tag{23}$$

2.4 Mitigation of the Barriers

In this section various methods of mitigating noise, attenuation, fading, multipath propagation etc. have been discussed.

2.4.1 Basic Impedance Matching

The maximum power-transfer theorem says that to transfer the maximum amount of power from a source to a load, the load impedance should match the source impedance. In the basic circuit, a source may be dc or ac, and its internal resistance (R_i) or generator output impedance (Z_g) drives a load resistance (RL) or impedance (Z_L) as shown in fig below.

However in real time applications load and source impedance don’t match so it is necessary to provide an impedance matching circuit to achieve maximum power transfer from source.

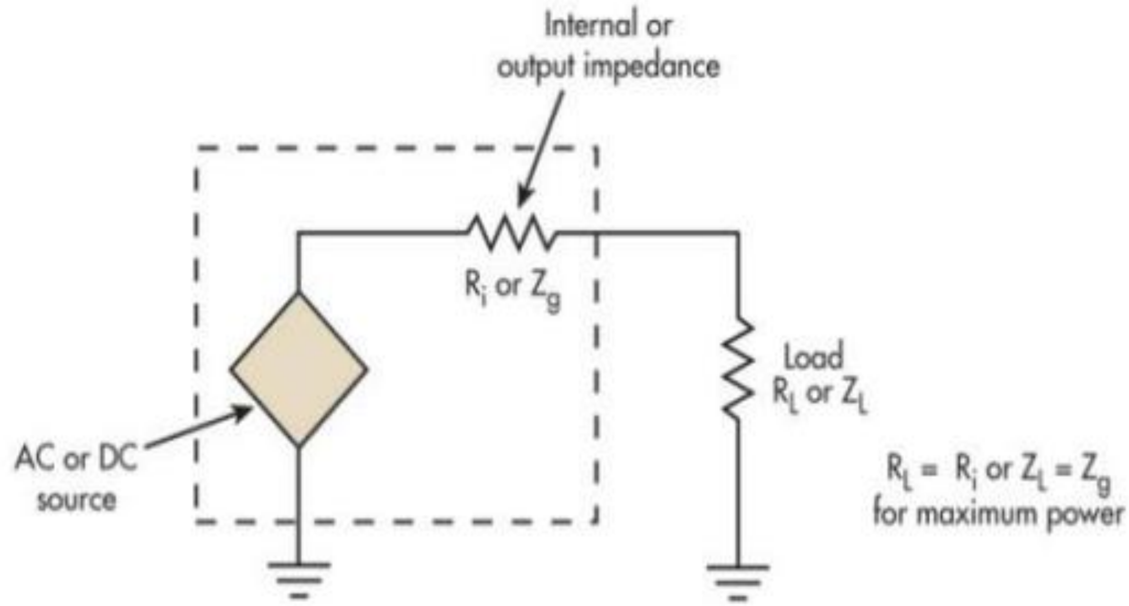

Fig 2.9: Basic electrical circuit

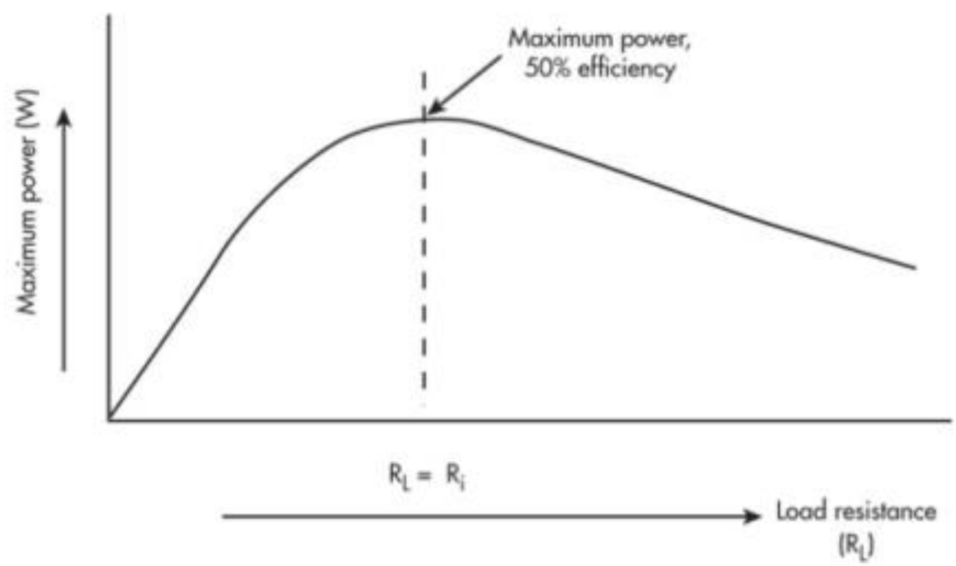

Fig 2.10: Plot of source power vs. load resistance

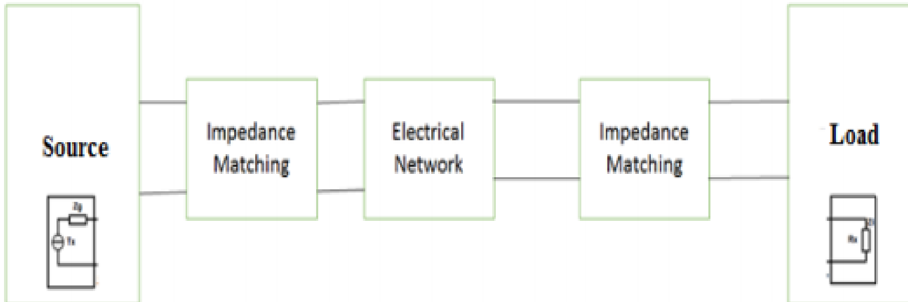

Fig 2.11: Basic layout of impedance matching

2.4.2 Choosing the appropriate modulation technique

The choice of modulation scheme is dependent on the nature of physical medium on which it has to operate. Modulation schemes for use on power lines should have the following desirable properties:

- → Ability to overcome non-linear channel characteristics.
- → Ability to overcome multipath spread.
- → Ability to adjust dynamically.
- → Ability to mask certain frequencies.

Among all the modulation techniques, OFDM is widely accepted in Power Line Communication due to its noise resilience, less effect inflicted by Multipath fading etc.

2.4.3 Using Noise Modeling

Different types of noise modeling can be used such as,

- Asynchronous Impulsive Noise Modeling
- Cyclostationary Impulsive Noise Modeling
- Non-parametric impulsive noise estimation etc.

This models estimates the nature of noise and tries to counter it.

2.4.4 Impulse Noise Modeling

Asynchronous impulsive noise forms one of the main challenges for high speed communications over power lines. Practice shows that this type of noise can have large energy leading to a significant degradation in the performance of PLC systems. The fact that impulsive noise may frequently sweep complete data symbols concerns researchers and designers of PLC devices and systems. In practical measurements in power lines found that the typical strength of a single impulse is more than 10 dB above the background noise level and can exceed 40 dB. Measurement results in indicate that the PSD of impulsive noise generally exceeds the PSD of background noise by a minimum of 10 −15 dB in most parts of the frequency band 0.2 − 20 MHz According to their measurements, this difference may rise to more than 50 dB at certain portions of the band.

The figure below shows a sample impulse having a duration of approximately 50 μsec. In the time domain, three random variables characterize the impulsive noise that occurs in power lines and other communication mediums.

These are: impulse width, amplitude and inter-arrival time (IAT). The impulse width and amplitude both identify the energy of a single impulse. The frequency of the impulses (the reciprocal of the IAT) along with the impulse energy describe the power of impulsive noise. Different statistical approaches attempting to model impulsive noise can be found in the literature. Background noise on the other hand is usually modeled as white Gaussian noise (WGN). In this section, some of these models to gain more understanding of the characteristics of impulsive noise will be observed.

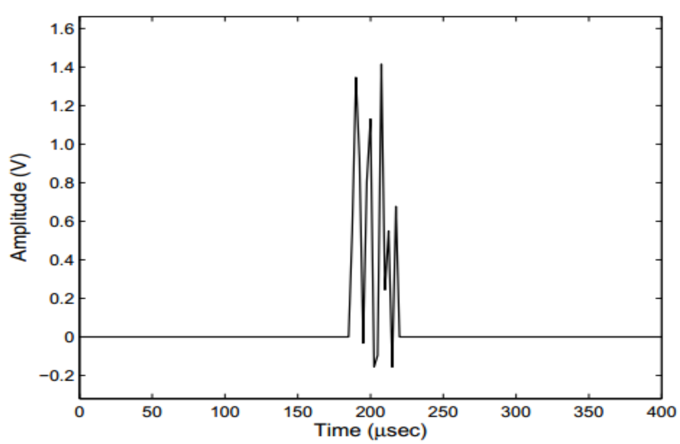

Fig 2.12: Sample impulse

2.4.5 Using Error correction coding and compressed sensing algorithms

Among various compressed sensing algorithms, sparse Bayesian learning (SBL) has become increasingly attractive due to its improved robustness over deterministic approaches such as Basis Pursuit

2.4.6 Time-domain Methods

The effect of impulsive noise in multicarrier signals can be reduced by preprocessing the time-domain signal at the front end of the receiver using a memory less nonlinearity. Owing to their simplicity, nonlinear techniques including clipping, blanking and clipping/blanking are often used in practical applications. The function of this kind of techniques is based on the assumption that the amplitudes of impulsive noise are often distinguishably greater than the signal amplitudes. Therefore, a threshold is defined and the signal samples that have amplitudes greater than the threshold are assumed to be affected by impulsive noise and hence modified according to the used nonlinearity. Fig. 2.14 illustrates a simplified block diagram of an OFDM system implementing a nonlinear technique to mitigate impulsive noise. The figure shows that the memory nonlinearity identifies both the amplitude and phase of the received signal, but only modifies the amplitude while the phase of the signal is kept unchanged.

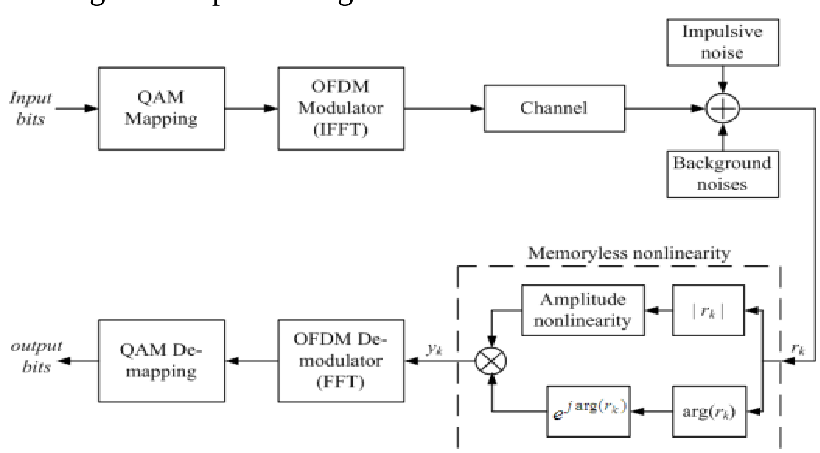

Fig 2.14: Simplified block diagram of an OFDM system employing a memory less nonlinearity for impulsive noise reduction

2.4.7 Time/Frequency Domain (TFD) mitigation configuration

Another technique of impulsive noise mitigation in PLC is the combined mitigation at both time and frequency domains.

Frequency domain (FD) mitigation is applicable only in situations when signal is to be classified/detected alongside wit parameter estimation, with the objective of compensating for average noise effect on the sampled signal. In this domain, the noise effect varies in the mean of the signal's power spectrum. Mitigation in frequency domain takes place after the OFDM demodulation and an under an assumption of ideal channel estimation. It involves the following steps;

- ✓ Estimation of frequency domain representation of impulsive noise corrupted by AWGN.
- ✓ A noise compensator then estimates the number of samples affected by the impulsive noise and
- ✓ Reconstruct the impulsive noise vector using a peak detector.
- ✓ The estimated impulsive noise is then subtracted from the equalizer output

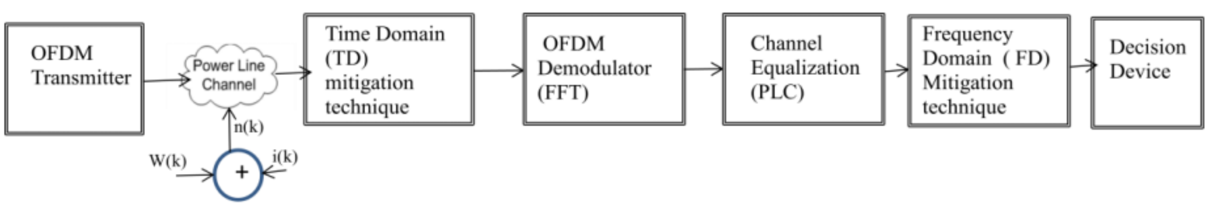

Fig 2.15: Time/Frequency Domain (TFD) mitigation configuration

2.4.8. Employment of multi carrier modulation technique

In addition to wireless medium, multipath propagation also happens in wired media especially where impedance mismatch causes signal reflection. A well-known example is power line communication.

High-speed power line communication systems usually employ multi-carrier modulations (such as OFDM or Wavelet OFDM) to avoid the intersymbol interference that multipath propagation would cause.

The ITU-T G.hn standard provides a way to create a high-speed (up to 1 Gigabit/s) local area network using existing home wiring (power lines, phone lines and coaxial cables). G.hn uses OFDM with a cyclic prefix to avoid ISI. Because multipath propagation behaves differently in each kind of wire, G.hn uses different OFDM parameters (OFDM symbol duration, Guard Interval duration) for each media.

2.5 Modulation Schemes use in PLC system

The properties of power line networks and the vulnerability to various types of noise calls for a proper selection of modulation schemes to be used in PLC systems.

Three major issues must be taken into account when selecting a modulation scheme for PLC:

• The susceptibility to different types of noise including impulsive noise with relatively high noise power leading to lower SNR.

• The PLC channel is a time varying channel with frequency selectivity.

• Due to electromagnetic compatibility issues, the transmit power in

PLC systems is limited to relatively low levels.

In this section of the thesis, some of the candidate modulation schemes for PLC systems are discussed.

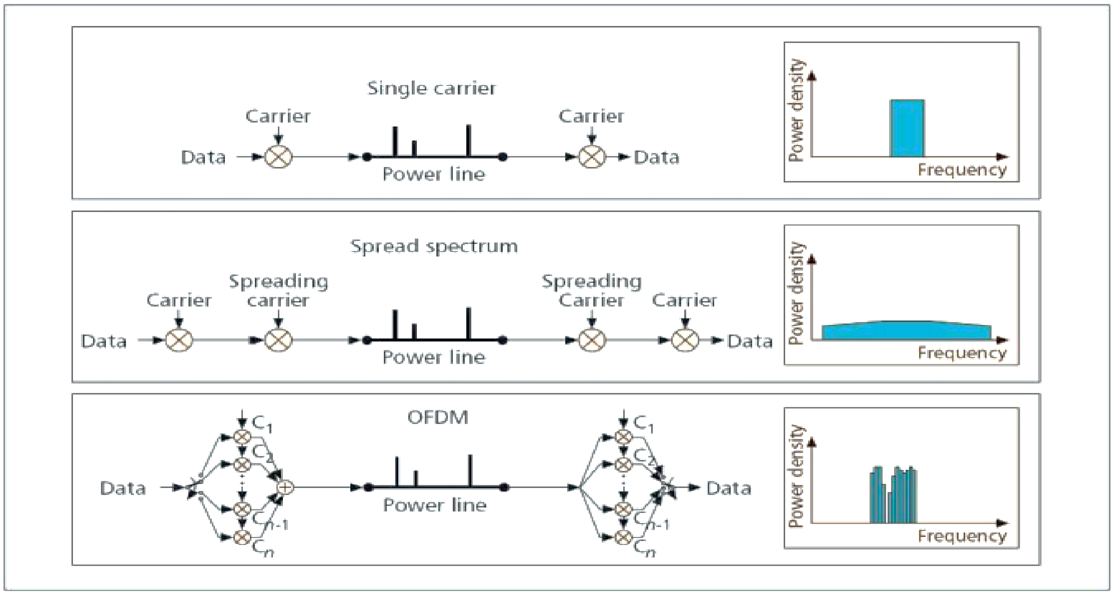

Fig 2.16: Modulation methods for power line communications

2.5.1 Single Carrier Modulation

In single-carrier modulation, the data signal modulates a single carrier with frequency f_0. The information is encoded in amplitude, phase or frequency of the carrier. In ASK (Amplitude-shift keying), the message signal modulates the amplitude of the carrier signal without affecting its frequency and phase, whereas in FSK (Frequency-shift keying) the frequency of the carrier is modulated. PSK (Phase-shift keying) is achieved by changing the phase of the carrier signal according to the information bits. A combination between PSK and ASK produces QAM (Quadrature-amplitude modulation). The top figure shows the constellation diagram of rectangular 4-QAM, while the middle and bottom plots illustrate the rectangular 16-QAM and 32-QAM respectively. Single-carrier modulation schemes are attractive candidates for PLC systems mainly due to their simplicity. For narrowband applications of PLC, single-carrier modulation is a convenient option and has been adopted in practical applications. For broadband PLC, however, these schemes have been found to be insufficient for high-speed communications through power line channels .This is attributable to several factors related to the transmission characteristics of the power line channel.

First, the multipath effect in this channel causes significant inter-symbol interference (ISI) and introduces deep notches in the frequency domain of the transfer function representing frequency-selective fading. The affected frequencies may vary with time and location according to the properties and structure of the used power line network. In the presence of such unpredictable frequency-selective fading, the performance of single-carrier modulation can be very poor. To elevate the performance and minimize the effect of ISI, powerful detection and equalization techniques have to be employed, which cancels out the simplicity feature associated with single-carrier schemes.

2.5.2 Spread spectrum technique

Spread spectrum techniques (SST) were initially developed for military applications with the aim of achieving robustness against intentional interference by spreading a narrowband signal over a wide frequency spectrum. For PLC applications, the interest in SST is due to its ability to combat frequency-selective fading introduced by the multipath effect as well as its robustness against all kinds of narrowband interference. In addition, SST is an attractive option for PLC because of the low power spectral density (PSD) of the transmitted signal, which concurs with the constraints related to EMC. There are several variants of SST including direct-sequence spread spectrum (DSSS), frequency hopping, time hopping, and chirp and hybrid techniques. The media access in SST can be achieved by code division multiple access (CDMA) without the need for global coordination and synchronization. In SST, a single carrier with frequency f_0 is first modulated with the information using conventional modulation methods producing a bandwidth that is approximately double the message bandwidth. Then a second stage of modulation is performed using a high-speed pseudo-random sequence. After this modulation, a bandwidth of about twice the clock frequency of the pseudo-random sequence is obtained. At the receiver side, the same sequence used in the transmitter must be known and synchronized with the received signal. After that the resulting signal is demodulated conventionally to obtain the message signal.

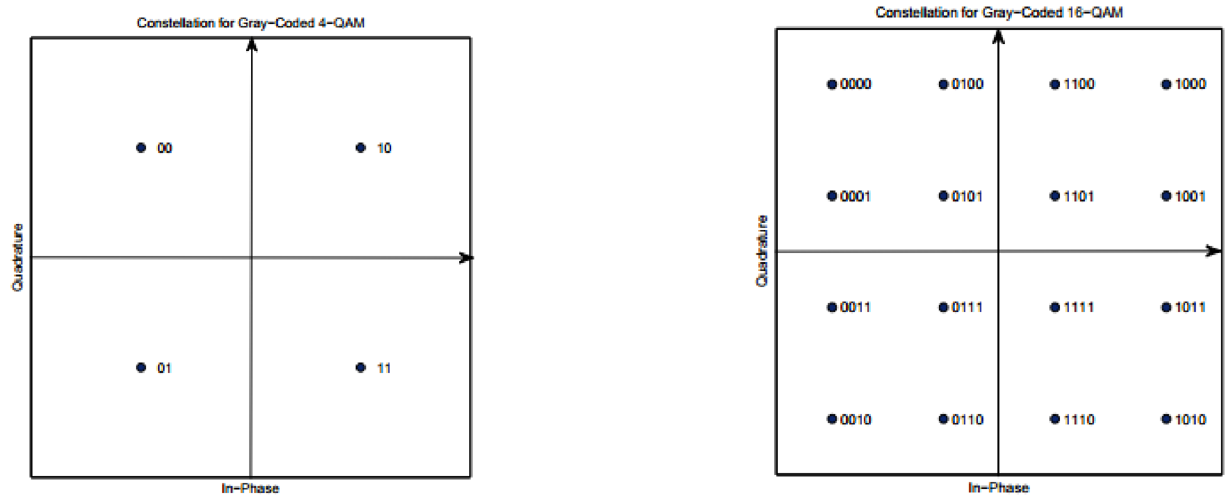

Fig 2.17: Constellation diagrams for QAM modulation with different sizes

2.5.3 Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is a mature multicarrier technique that has been well-proven in several high-speed wired and wireless applications. Examples of its applications include digital audio broadcasting (DAB), digital video broadcasting (DVB), asymmetric digital subscriber line (ADSL) and Wi-Max. OFDM offers added spectral efficiency as well as robustness against selective fading, narrowband interference and impulsive noise which makes it an attractive contender for high-speed communication systems.

The basic principal of OFDM is to segment a high-speed serial data stream into numerous parallel low-speed streams that are carried simultaneously over multiple orthogonal sub channels.

Using parallel transmission, the increase in the time length of each low-speed symbol allows it to combat the inter-symbol interference (ISI) caused by multipath delay. To eliminate ISI completely, a cyclically extended time guard is appended at the beginning of every OFDM symbol.

In OFDM, the parallel data streams are first mapped into PSK or QAM symbols which then modulate a number of subcarriers using discrete Fourier transform (DFT) producing an OFDM signal. An OFDM symbol starting at $t = t_s$, carrying a sequence d_i of QAM symbols in N subcarriers can be expressed by the following complex baseband representation.

$$s(t) = \sum_{i=-\frac{N}{2}}^{\frac{N}{2}-1} s_{i+\frac{N}{2}} \exp\{j2\pi \frac{i}{T}(t - t_s)\} \quad , \quad t_s \le t \le t_s + T \tag{24}$$

$$s(t) = 0 \quad , \quad t < t_s \quad \wedge \quad t > t_s + T \tag{25}$$

Where T is the symbol duration.

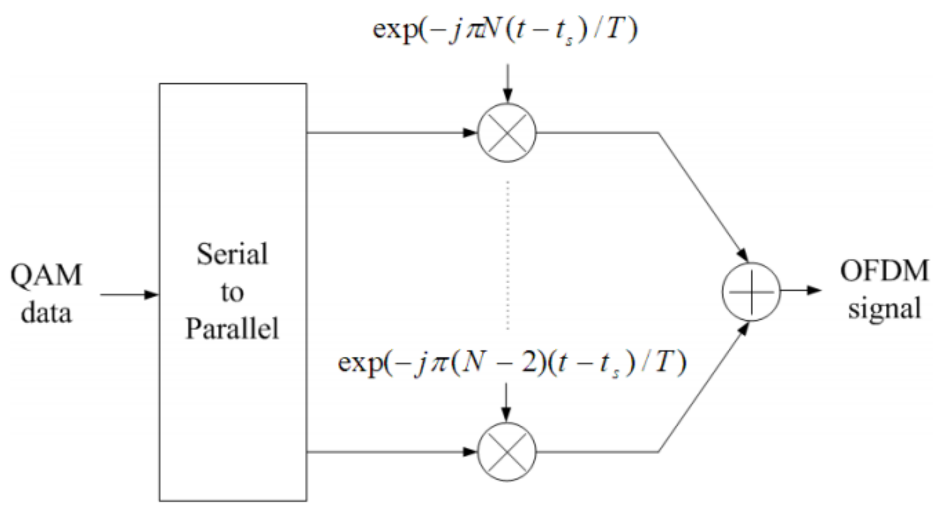

Fig 2.18: The modulation of multiple subcarriers in OFDM

The simple and efficient implementation of OFDM gives it an advantage over other multicarrier modulation schemes.

$$s(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} S_k e^{j2\pi\frac{k}{N}n} \quad , \quad n = 0,1,2, \ldots\ldots, N-1 \tag{26}$$

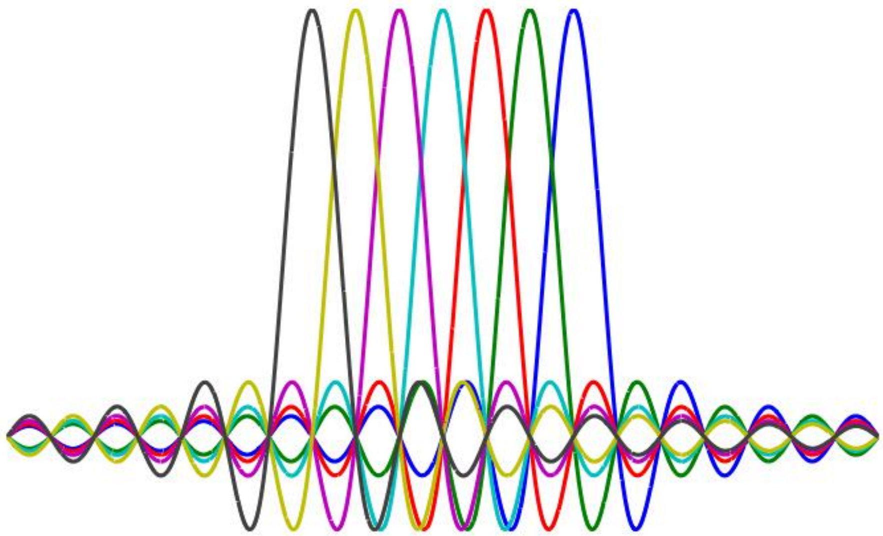

Fig 2.19: Frequency spectra of individual subcarriers in one OFDM symbol

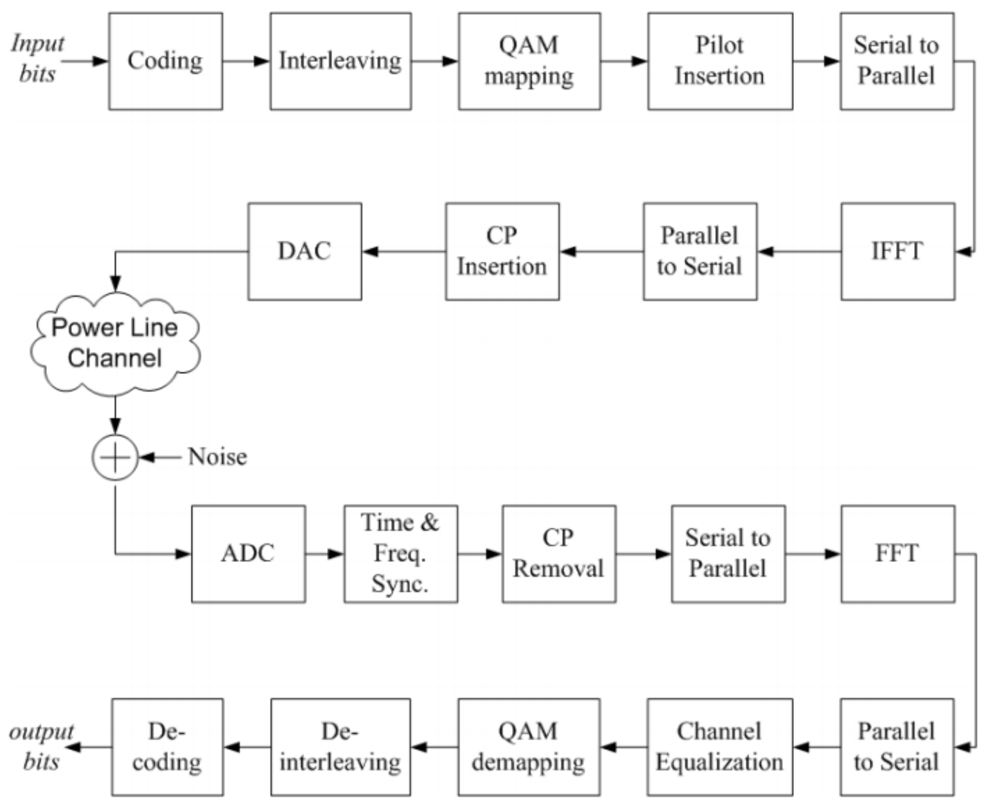

Fig 2.20: Block diagram of an OFDM system consisting of a transmitter, a PLC channel and a receiver

2.5.4 Adaptive modulation

A key benefit of using OFDM in PLC and various wired and wireless systems is its capability to effectively convert a broadband frequency-selective channel into narrowband flat-fading sub channels. Thus, the channel equalization complexity at the receiver can be minimized. PLC systems are vulnerable to narrowband interferences generated by AM broadcasters and other sources in addition to the frequency-selectivity characteristic introduced by branching and impedance mismatches. In conventional OFDM systems, all subcarriers are assigned the same constellation size and transmit power level. Therefore, if a sub channel or a group of sub channels are severely faded, they would dominate the overall bit error rate (BER) of the system resulting in a significant performance degradation.

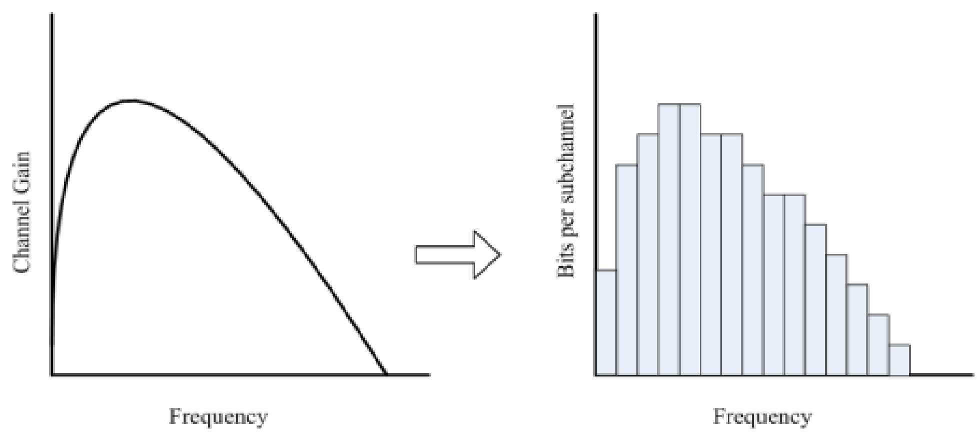

Fig 2.21: Basic concept of adaptive modulation by adjusting the constellation size according to the channel conditions

To improve the performance of high-speed OFDM-based PLC systems, adaptive modulation methods can be employed so that each sub channel can have a different constellation size and/or a different transmit power depending on its fading conditions. Fig. 2.21 shows the basic concept of adaptive modulation, where each sub channel carries a different number of bits depending on its gain and noise conditions. Adaptive modulation has been proven to improve the performance of multicarrier systems significantly. In adaptive modulation, several parameters can be controlled and adjusted to the sub channel signal-to-noise ratio (SNR). These include:

• Data rate

• transmit power

• Instantaneous BER

• Constellation size

• channel code or scheme

Subcarriers that are excluded from the usable bandwidth due to regulations or interference with other wireless applications can be nulled by assigning zero power and distributing the data among the usable subcarriers. To ensure a significant improvement using adaptive modulation, a reliable feedback channel supplying up-to-date channel state information from the receiver end to the transmitter end can be utilized. This can be accomplished by inserting know pilot symbols in time or assigning particular subcarriers for channel estimation.

Based on their objective function, the algorithms can be classified in two main categories:

• Margin-adaptive (MA) algorithms that endeavor to minimize the overall transmit power level. MA algorithms often have data rate and BER constraints that they have to maintain.

• Rate-adaptive (RA) algorithms that strive to maximize the overall data rate given transmit power and BER constraints.

Some loading algorithms aiming at minimizing the BER of a system where reliability is of major priority can also be found in the literature.

An example of this is the algorithm proposed by Goldfeld et al. that guarantees minimal aggregate BER, where the constellation size is assumed constant among all the subcarriers.

In terms of their basic operation, most loading algorithms can be classified into three categories:

1. Incremental algorithms that incrementally allocate an integer number of bits to the subcarrier that has the lowest penalty in terms of the constraints until the maximum capacity is achieved without violating the power and/or BER constraints. This kind of algorithm is often called a greedy

algorithm due to the fact that it chooses the allocation that is best for the current step without regarding the global effect of its choice. An early example of incremental loading is the algorithm proposed by Hough-Hartog which starts with zero bits for all the subcarriers. Then bits are incrementally loaded to the subcarriers requiring the minimum incremental energy until the BER or power constraints are violated. Another form of incremental loading is the algorithm that starts off with all subcarriers allocated the highest constellation size. Then, bits are incrementally removed from the subcarriers that have the worst BER performance until the constraints are reached.

2. Channel capacity-based algorithms where a closed form expression of the channel capacity is used to approximate a non-integer bit allocation for the subcarriers. Non-integer numbers of bits have to be rounded to the nearest integer causing some deviation from the optimum solution. If the sub channel SNR (γ_i) is known at the transmitter side, the number of bits per sub channel b_i can be calculated using the following expression:

$$b_i = \log_2(1 + \frac{\gamma_i}{\Gamma}) \tag{27}$$

Where Γ is the SNR gap which represents how far the system is from achieving its maximum capacity.

3. BER expression-based algorithms that also use closed-form expressions to find the bit allocation and then round any non-integer values.

For example, if sub channel i is modulated by an M_i-QAM signal, then the probability of error in this sub channel when its SNR is γ_i can be approximated using the expression:

$$P_{M_i,i}(\gamma_i) = 4\left(1 - \frac{1}{\sqrt{M_i}}\right) Q\left(\frac{3\gamma_i}{M_i - 1}\right).[1 - (1 - \frac{1}{\sqrt{M_i}})]Q\left(\frac{3\gamma_i}{M_i - 1}\right) \tag{28}$$

Where Q (.) is the Q-function defined by the following:

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{\frac{-t^2}{2}} dt \tag{29}$$

Using the expression in (29), the BER for each subcarrier with all possible constellation sizes can be obtained given their SNR values, hence the constellation size that meets the sub channel BER constraints can be selected.

2.6 Error correction codes

The power line channel is considered a hostile medium for high-speed data communications suffering mainly from multipath fading, attenuation and various kinds of noise including high-amplitude impulsive noise. Despite that, studies on the capacity of this channel promise very high data rates. The use of OFDM as a transmission technique not only tackles impulsive noise, but also copes with some of the impairments of this channel such as frequency selectivity. In fact, the immunity against impulsive noise was one of the fundamental motives behind the renewed interest in using multicarrier modulations for digital communications.

OFDM is suitable for broadband applications because it uses numerous narrowband subcarriers that can be assumed to have a flat frequency response. In the case of impulsive noise, OFDM splits its effect between all the subcarriers during the demodulation process at the receiver.

Even with OFDM, in order for the PLC channel to exploit its capacity in full and provide broadband high-speed data rates, it is necessary to make use of effective channel coding schemes that are capable of combating impulsive noise and other channel impairments. Forward error correction (FEC) is implemented by adding redundancy bits to the useful data bits. The receiver can then use these redundancy bits to detect and possibly correct errors occurring during data transmission at the cost of lowering the useful data rate.

Different coding methods can be suitable for PLC systems. One of the well-known classes of coding is block coding, in which the data is divided into blocks of k data bits and each block is attached with the required redundant bits resulting in larger blocks of n bits. The code is then denoted (n, k).

The code rate defines the ratio k/n between the data bits and the total number of bits per block.

A well-known simple class of block codes are Hamming codes. Such codes are very suitable for low-speed indoor PLC. Hamming codes are capable of correcting all single errors and detecting combinations of two or less errors in a single block. Hamming codes can be decoded using Syndrome decoding.

Another well-known class of block codes is the BCH code. BCH codes are basically a generalization of the Hamming codes where multiple error corrections can be achieved. They are more powerful and have a large variety of block lengths, code rates, alphabet sizes and error correcting capabilities. BCH codes perform better than all other block codes with the same block length and code rate when using a block length of a few hundred. Many studies of impulsive noise in power line networks assume that impulsive noise arrives as independent and identically distributed (i.i.d.) complex random variables. However, impulsive noise can occur in bursts with durations that may be longer than the length of communication symbols. This burstiness of impulsive noise should be considered for a proper design of PLC systems, since coding schemes that are designed for individual errors do not appropriately correct burst errors. This problem can be solved by the use of interleaving. By rearranging the data bits, the interleaver distributes the errors among the transmitted data and reduces the channel memory. Consequently, the decoder sees the errors caused by bursts of impulsive noise as independent errors that are easier to control.

2.7 Applications of PLC

In the early days of the PLC technology, the use of electric grids for communication purposes was motivated by the need for a convenient communication link to maintain the function of power networks. The tasks of this link included mainly operations management, monitoring and troubleshooting. Then, other narrowband applications using PLC emerged including single-directional communications, like remote switching of public lights, and bidirectional communications such as meter reading and various home automation applications (e.g. intruder alarm, fire detection and so forth).

Nowadays, PLC technologies span a wide range of applications including voice, video, multimedia, networking and so forth; thanks to the increased demand for high data rate broadband applications. This section provides an overview of the current and prospective applications of PLC.

2.7.1 PLC-based Local Area Networks

A common and widespread application of PLC is to create a local area network (LAN) in the home or office using the indoor electric wiring. The driving advantage of PLC for this application is the availability of power sockets everywhere in the house or office which makes it easy to network various computers in one LAN using the already existing power lines. Similar to other LAN technologies, PLC-based LAN networks allow the sharing of files and printers, yet without the need for new wires. File and printer sharing is particularly important in professional computer networks.

Computers connected to one PLC network can share a single Internet connection. Regardless of the technology used to provide the Internet to the customer premises, a PLC device can reroute the data flow into the electrical network. This way, Internet access is made available to every outlet in the home or office. Fig. 2.22 illustrates a PLC-based local area network including file and printer sharing as well as an Internet connection shared by the network users. Broadcasting of data from different sources is another application of LANs based on the PLC technology. An example of this is broadcasting audio signals in different formats from an audio files server to all the computers connected to the electrical network at the home or office. In addition, audio devices can be interconnected with each other and to speakers using the PLC network. Other recreational applications like network games, which can be played between different stations in the network, can also use the PLC connection.

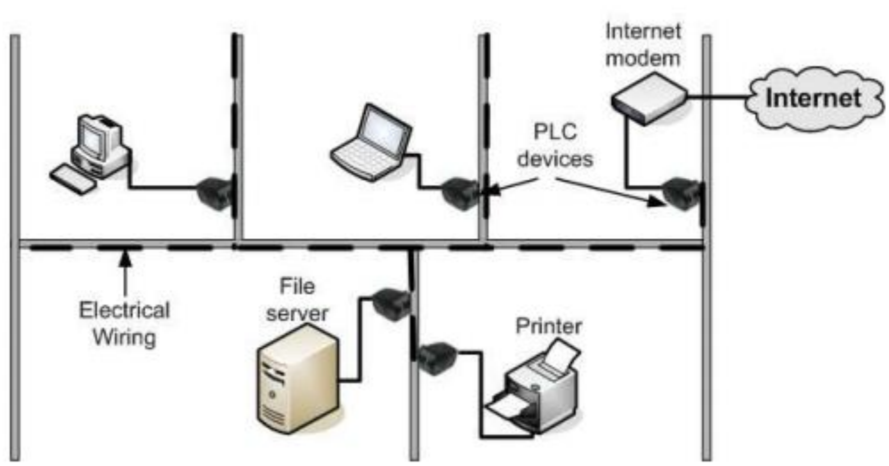

Fig 2.22: LAN network including file, printer and Internet sharing based on PLC.

PLC can be integrated with other LAN technologies in different ways. PLC can play the role of a backbone to the widely-used Wi-Fi networks as shown in Fig. 2.23. Although Wi-Fi networks provide mobility and flexibility to the users within a building, full coverage of large buildings may not be guaranteed without using multiple wireless routers interconnected via a wired backbone. The electric wiring can provide this backbone link between Wi-Fi routers using PLC devices.

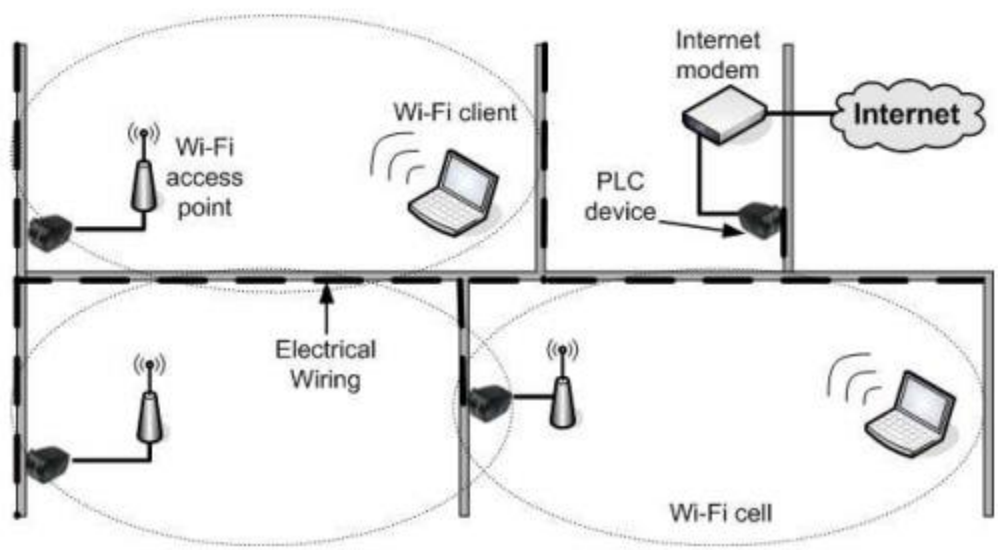

Fig 2.23: PLC used as a backbone for a Wi-Fi network.

2.7.2 Voice, Video and Multimedia

The high data rates offered by PLC can support applications like voice, video and multimedia. For example, telephony over PLC is one of the first applications using PLC and was first tested in 1918. The transmission of telephone speech requires a bit rate that can be as low as 5.6 Kbps, which can very easily be supported by PLC. However, the data rate is not the only concern for conveying telephone conversations over PLC. For a reliable application with human interaction, the maximum time allowed between the transmission of information and the reception of the same information is 300 ms. This means that the round trip of speech bits in a telephone conversation over PLC must not take more than 300 ms. In addition, synchronization at the receiver is another issue for voice communications over PLC. The transmitted information has to arrive at the receiver at precise synchronization times.

Voice can be transmitted through PLC as IP packets using VoIP (voice over IP) technique. Using this technique, the speech is partitioned into IP packets, which then travel over PLC and other networks. Access to the network is often managed using the CSMA/CA (Carrier sense multiple access with collision avoidance) protocol.

PLC can also support higher data rates suitable for video applications such as video streaming, video surveillance, cable TV and videoconferencing. If the application requires only single-directional flow of information, as in the case of video streaming, the time delay constraint can be relaxed.

The waiting time for the time when the source starts sending information and the time when the video is played at the receiving end can reach several seconds. This time allows the receiver to have sufficient packets in memory before viewing the video, hence avoiding interruptions during the video playing time. Another uni-directional application is video surveillance using power lines. The use of PLC for this application offers a great flexibility in relation to the location of the camera, since a power outlet has to be in close proximity to power up the camera. Another advantage achieved by PLC in this context is that there is no need for extra wires as in other wired technologies often used in video surveillance.

Video are often encoded using the MPEG standards. Depending on the employed compression technique and ratio, the quality of images constituting the video may vary. Generally, the lower the compression, the higher the image quality. Another important parameter affecting the quality of images is the achievable data rate that can be used to convey video image frames. For PLC based on recent standards like HomePlug AV and IEEE

1901, no difficulties should exist in terms of the data rate requirements for video transmission with television quality, so long as the PLC network is not excessively used. HDDTV (high-definition digital television) can also be supported by these PLC standards. However, due to the high bit rate required for HDDTV ($5 - 10$ Mbps), the number of users in a network is very limited. Earlier PLC standards like HomePlug 1.0 have limited data rate capabilities and cannot support HDDTV.

Videoconferencing is another function that can be employed using PLC systems. In order to have a quality as good as television, high data rates of several megabits per second are required. For cinema quality videoconferencing, the required data rate can be as high as 50 Mbps. As in the case of telephony over PLC, videoconferencing includes human interactivity, which imposes the time delay constraint (300 ms for a round-trip).

Synchronization is another concern for video conferencing and has to be controlled effectively. The PLC technology also supports the transmission of multimedia files incorporating speech, video and other data types. Multimedia applications normally need high bit rates depending on the types of data included. High data rates can be provided using PLC devices based on the recent standards. However, when transmitting multimedia files, it is necessary to synchronize the simultaneous applications that comprise a multimedia process.

2.7.3 Internet Access

The PLC technology can use the LV power grids as an access network providing Internet and other IP services to customers in the last-mile area.

This is achieved by injecting the PLC signal into the LV power grid using a PLC device (Master). Fig. 2.24 illustrates this scenario. In the subscriber end, another PLC device (Slave) retrieves the Internet signal and distributes it into the in-building electric network, where different communication devices can use the power sockets to gain access to the network.

The communication is controlled by the master PLC device which is located near the MV/LV transformer. This master PLC equipment acts as a base station for the subscribers' PLC devices. The communication between this base station and the wide area network (WAN) can be achieved by conventional communication methods such as optical fibers, radio links and so forth or by the use of MV power grids.

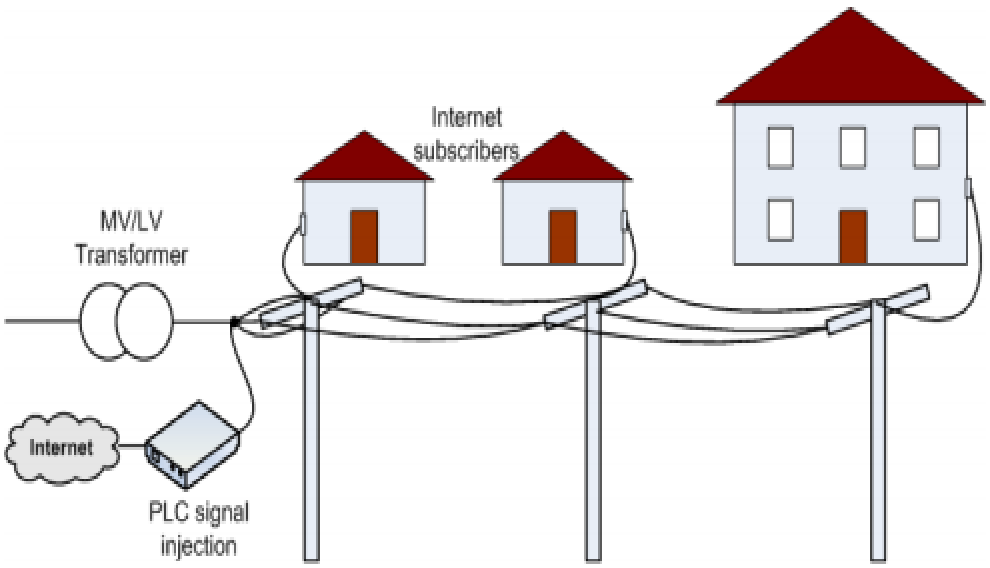

Fig 2.24: PLC used to provide Internet access to the subscriber in the LV network.

Chapter 3: Physical Implementation of PLC Model

3.1 Circuit Details

In this section, several practically Implemented PLC circuit designs have been discussed with their diagram and simulations.

3.1.1 Design of Coupler

Coupler is considered as the heart of a power line communication. The coupling can be done in several ways. Such as optocouplers, transformers etc. Here Ferrite core transformer has been used in the circuit.

Transformer coupling circuit is used in the power line communication model because transformers provide galvanic isolation from power line and act as limiter when saturated by high voltage transient. Reasons for using ferrite core is that it has high magnetic permeability, thus low eddy current loss for high frequency carrier signal.

For survey purpose the voltage of power line has been stepped down from 220V to 12V. In order to do so a regular step down transformer have been used. The amplitude of the high frequency signal was taken 5V. The ferrite core transformer had 120 turns in primary winding and 50 turns in secondary winding which provides a turn ratio of 12V:5V. Capacitor provides high impedance for low frequency signals and low impedance for high frequency signals. Similarly inductors provide low impedance for low frequency signals and high impedance for high frequency signals. Due to this property combination of series capacitors and parallel inductors were used to design high pass filters.

The capacitor pass the high frequency signal and block the low frequency signals. The small amount of low frequency that passes through the capacitor will be eliminated by the inductor in parallel connection which shorts the low frequency signal. This capacitor and inductor forms multiple order filter which improves the waveform. In addition, parallel resonant circuits can be used here to improve overall bypass effect. For transmitting high frequency signal live-neutral is connected to power line and input side is connected to low voltage high frequency source.

The cut off frequency was calculated to 1MHz which means only signals above this frequency range will pass through the circuit. This signal will be coupled to the power line by the ferrite core transformer but the low frequency voltage of power line will be blocked by the filters. This will cause the high frequency signal to pass through the power line along with the AC voltage of power line. A similar circuit is used to retrieve the high frequency signal from the power line. For transmitting signal through coupler circuit, high frequency signal flows from input side to live-neutral and flows in reverse direction for receiving signal.

This circuit can be modified to couple high frequency signal direct to a 220V power line. In such case the peak to peak value of high frequency carrier signal was taken 10V. The ferrite core transformer had 2200 turns in primary winding and 100 turns in secondary winding which provides a turn ratio of 22V:1V. Back to back zener diodes are used here to clamp the voltage transients at the secondary side of the transformer and limiting any high voltage that may creep into the coupler circuit. A resistor is connected in parallel with the capacitor to discharge the capacitor in order to minimize the hazard of high voltage peaks caused by the stored charge in capacitor. The metal oxide varistor (MOV) protects the circuit from any incoming surge from the power line; basically the metal oxide varistor provides protection against very large transients on the power line.

This section will discuss about the circuit that has been designed for the purpose of establishing an analytical model of a power line communication system and verification of transit-receive capability. At first a discussion about the special components used in this design such as ferrite core transformers, line traps etc. is given.

3.1.2 Ferrite core transformers

Ferrite core transformers are used because of their high magnetic permeability and it provides galvanic isolation which is essential in the circuit. Also it is very much effective in high frequencies than general transformers. It also provides low losses at high flux density and temperature as well as shows good stability at low condition. The experiment needed losses as lower as possible.

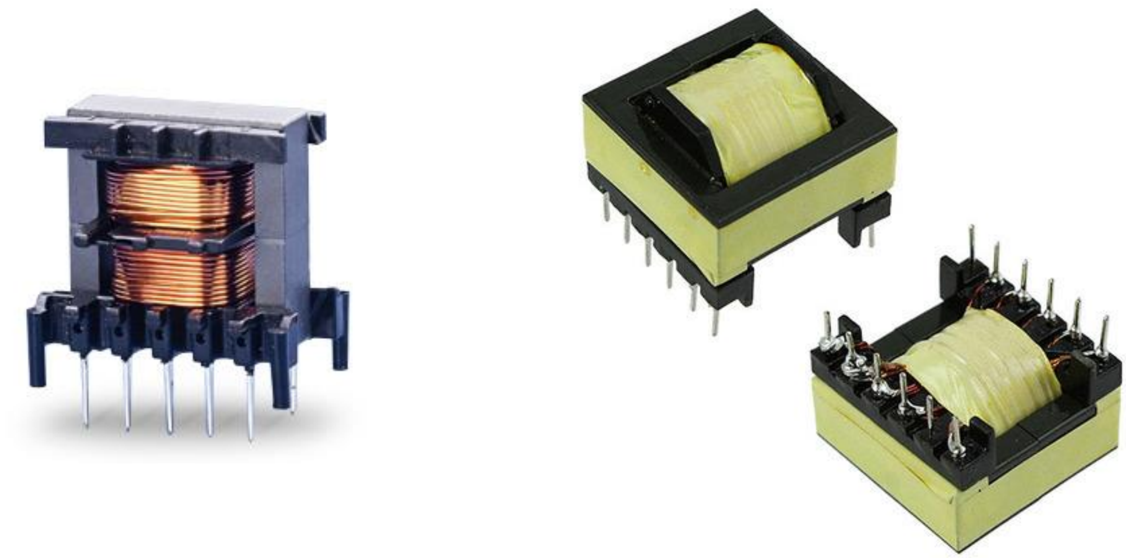

Fig 3.1: Ferrite core transformers

The solid steel core gets hot soon and there is a possibility for the wire insulations meltdown. This heat is eddy current losses. Plus such a core has a relatively low frequency range in which it can operate.

Another advantage of ferrite core transformer is that the core itself is nonconductive. As a result the eddy currents flow is very little. Disadvantage is that these sintered materials have low maximum field strength about 0.4T where steel has almost 1.3T. But the low field strength is not a matter of concern since the ferrite core can work in high frequencies instead of 50 Hz. It is a fast material, but at low field strengths. So in other words, ferrite shines at high frequency. But it is not much effective at low frequencies like 50 Hz due to the low max field strength.

3.1.3 Line trap circuit

The line trap used here is a multiple-T-filter configuration, which is made up of coils and capacitors. It is connected in series with the power line and presents high impedance to the carrier band of 1 MHz to 15 MHz, the T-filter configuration is chosen because of its advantage of working well in low impedance line.

The transmission (ABCD) parameters of the trap can be written as,

$$A = D = (1 + 2\omega^2 L_2 C_1 + \frac{\omega^4 L_2^2 C_1^2}{4}) \quad (30)$$

$$B = (2\omega L_2 + \frac{3}{2}\omega^3 L_2^2 C_1 + \frac{\omega^5 L_2^3 C_1^2}{4} \quad (31)$$

$$C = (2\omega C_1 + \omega^3 L_2 C_1^2) \quad (32)$$

The configuration of the line trap circuit that has been used in the design is shown below along with the matlab Simulink images.

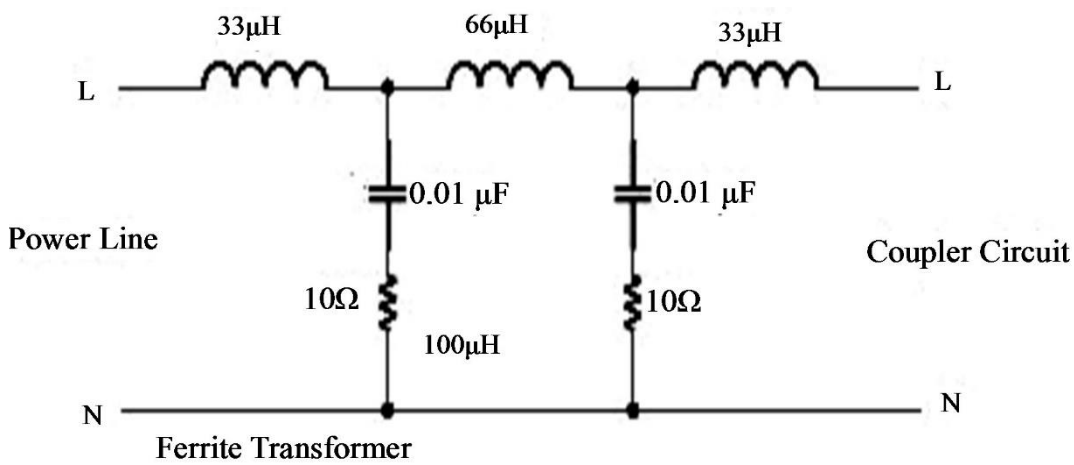

Fig 3.2: Line trap circuit

The circuit implemented in Simulink-

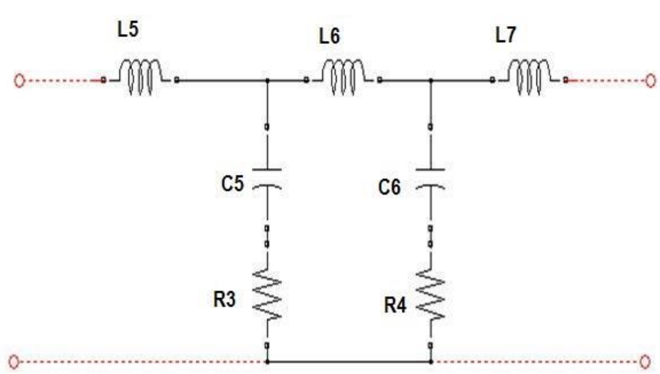

Fig 3.3: Line trap circuit in Simulink

3.2 Operation and implementation of the designed circuit

An implementation of several circuits for analysis and several variations is described below. For example test results of the designs with or without line traps and analyzed outcomes of the differences are verified.

The circuit is implemented on low voltage (12V-20V). But similar design with slight difference can be used for high voltage (220V).

The fundamental circuit chosen for the analysis is,

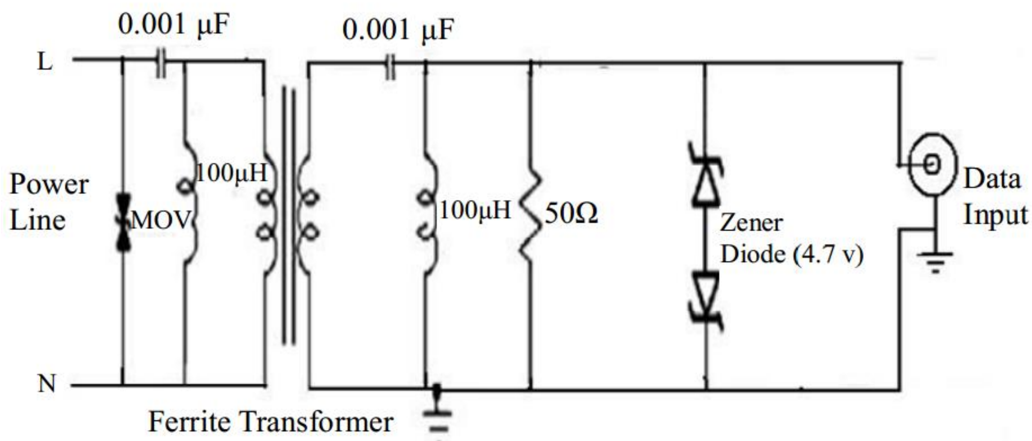

Fig 3.4: Low voltage bi directional PLC circuit

The circuit shown above is bi directional it means that data signal can be sent and received simultaneously using the same circuit.

The works have been limited in low voltage. But a slight modification of this circuit can be used for high voltage.

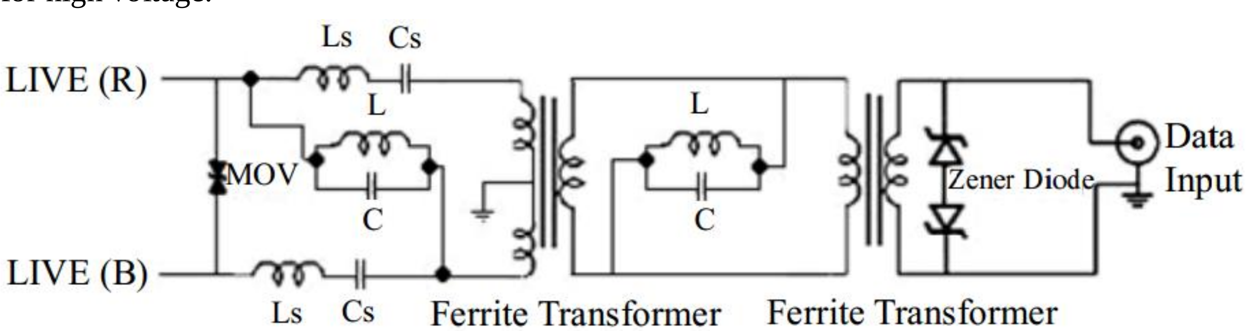

Fig 3.5: High voltage bi directional PLC circuit

3.2.1 Bi directional coupler-decoupler circuit without Line traps

An attempt has been taken to implement a bi directional PLC circuit without Line Traps. The circuit has been simulated in Simulink and analyzed for the output waveforms.

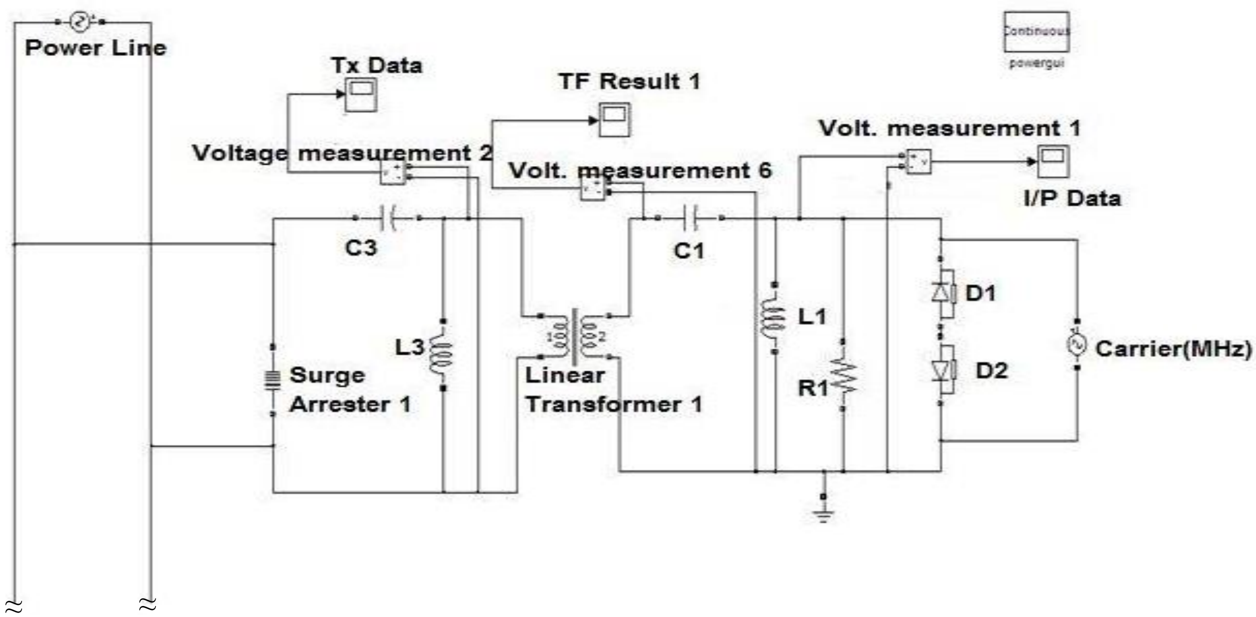

Fig 3.6: Simulink circuit for transmission side of the PLC circuit (w/o Line Traps)

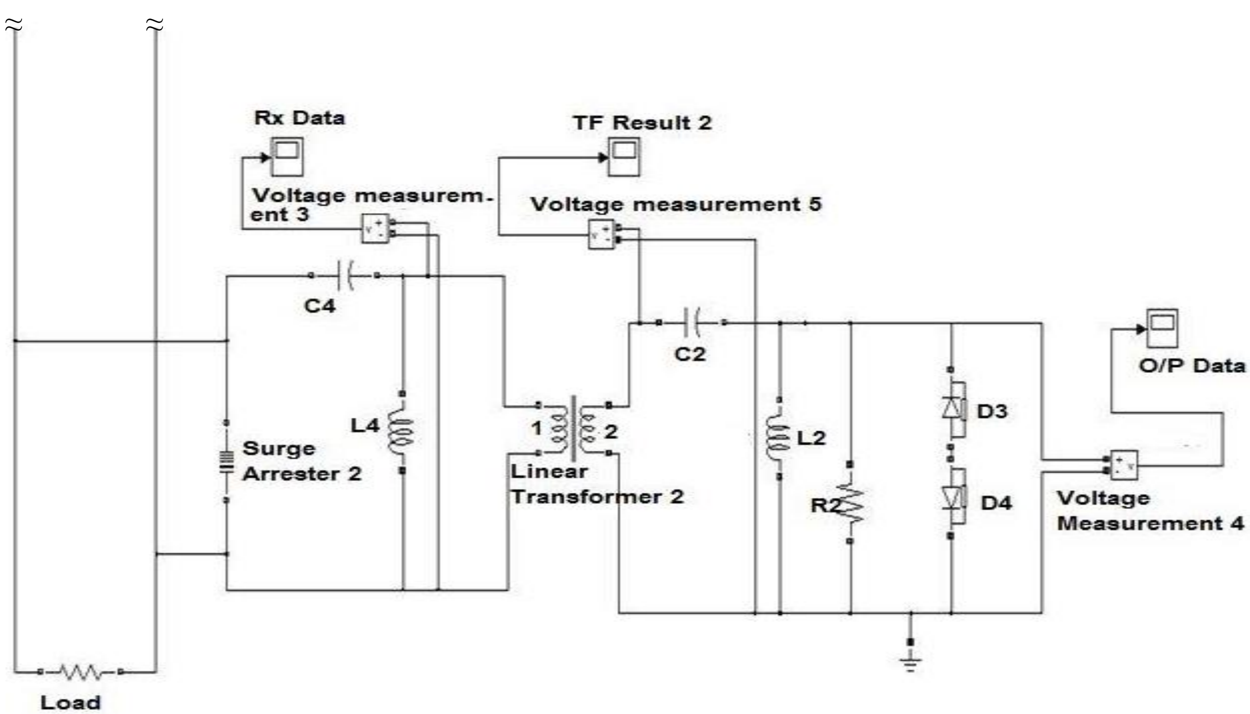

Fig 3.7: Simulink circuit for receiving side of the PLC circuit (w/o Line Traps)

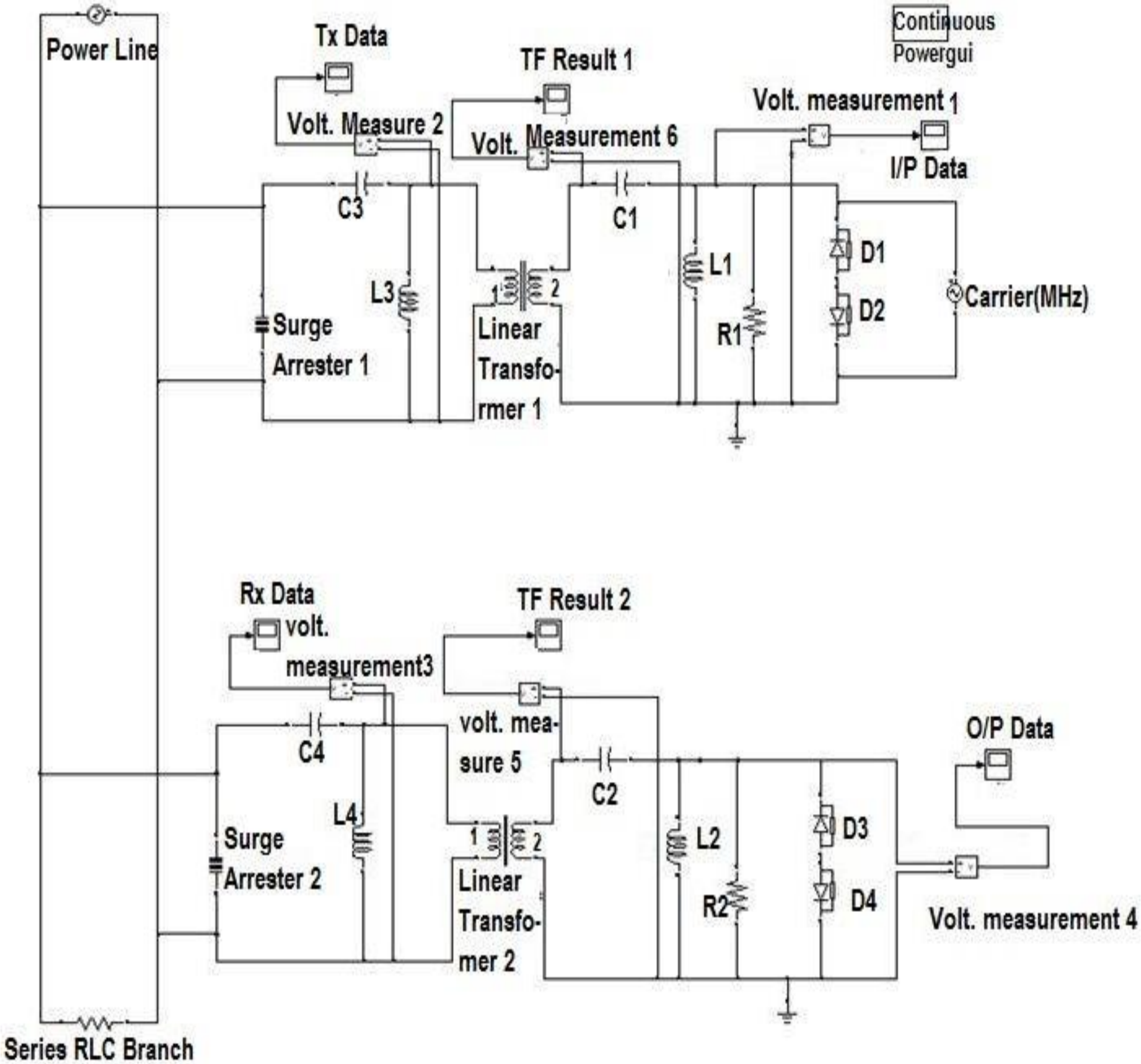

Fig 3.8: Simulink circuit for overall PLC circuit (w/o Line Traps)

The resulting waveform found after simulation:

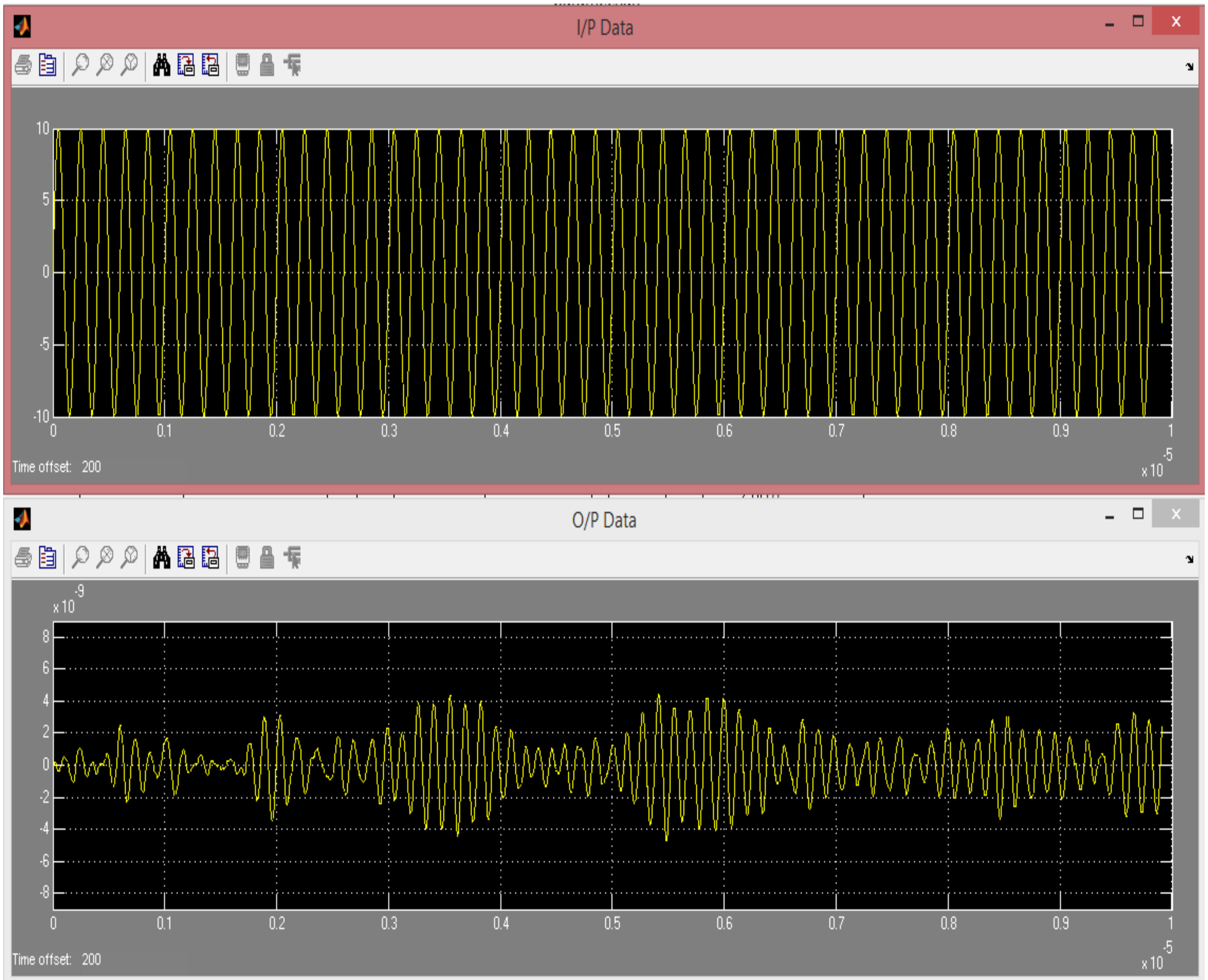

Fig 3.9: Simulink output of implemented circuit

3.2.2 Bi directional coupler-decoupler circuit with Line traps

The circuit implemented above was also analyze with line traps. The line trap used here is a multiple-T-filter configuration, which is made up of coils and capacitors. , the T-filter configuration is chosen because of its advantage of working well in low impedance line.

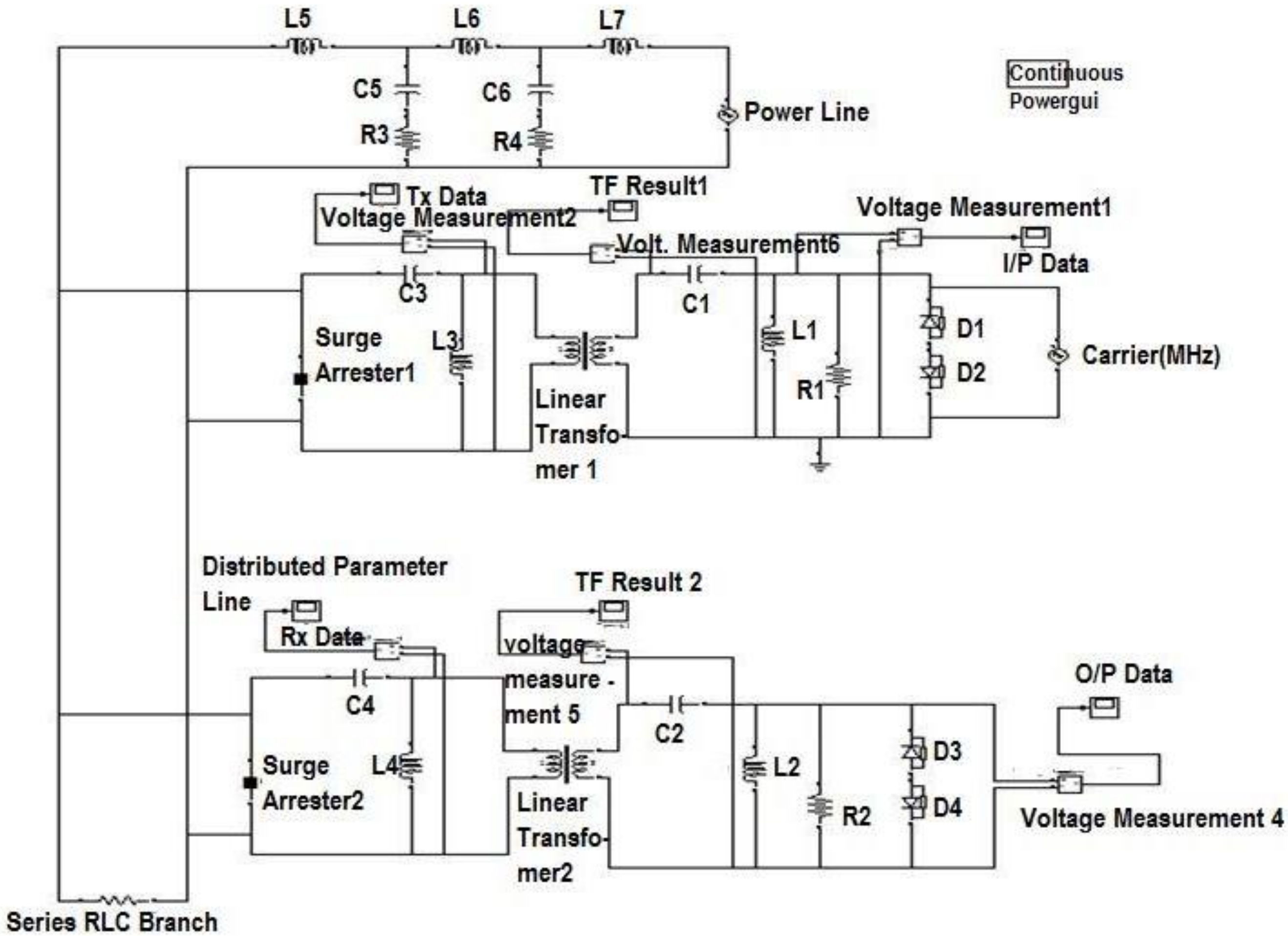

Fig 3.10: Simulink circuit for overall PLC circuit (with Line Traps)

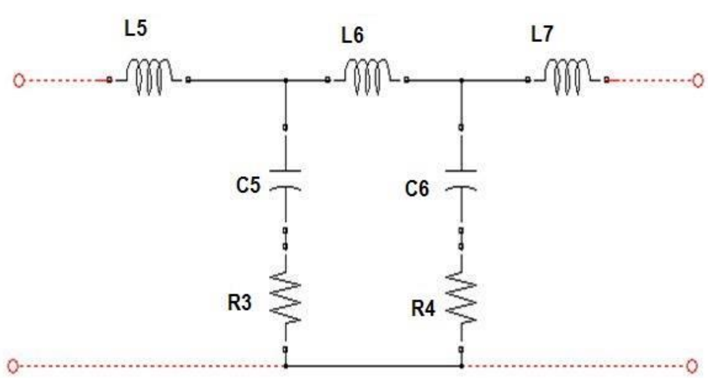

Fig 3.11 Line trap circuit

3.2.3 Simplified Bi directional PLC circuit

In addition to circuits explained above, a simplified PLC circuit has been implemented and also the result has been tested practically.

It is basically an all in one coupler-decoupler circuit that can send and sense signals simultaneously.

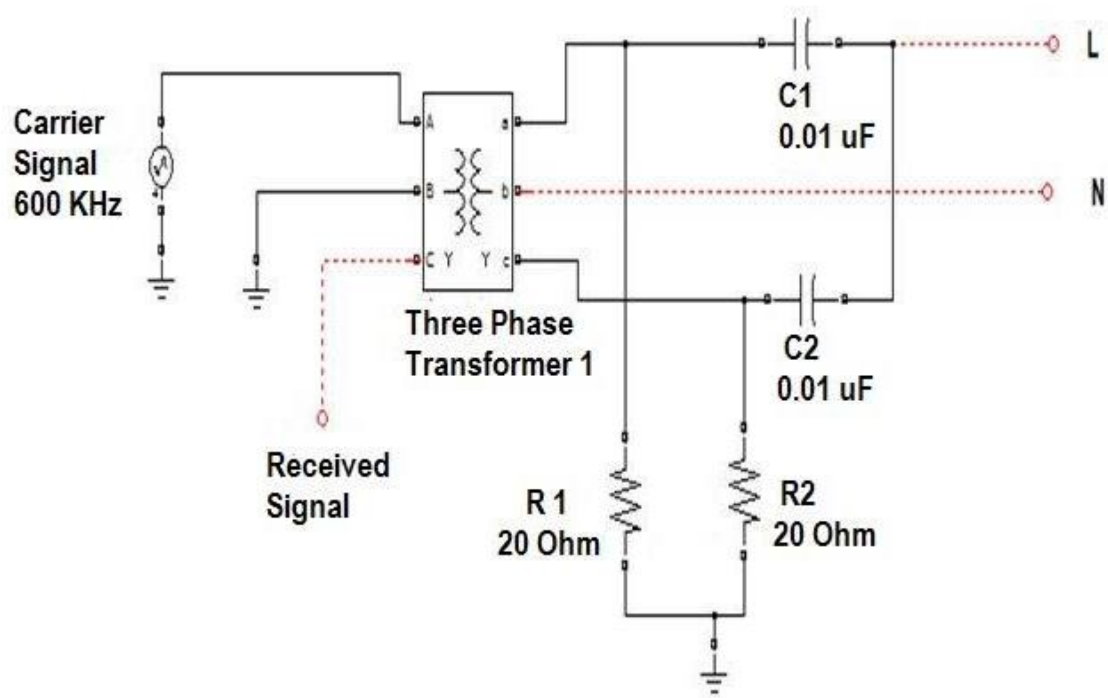

Fig 3.12: Simplified PLC circuit for practical implementation

Transformer-capacitor coupling circuits are used exclusively in low-voltage power-line communications as the transformer provides galvanic isolation from the power line network. Additionally the transformer acts as a limiter when saturated by high-voltage transients. As power-line access impedances are generally very low, poor power transfer is achieved because of the mismatch between signal power impedance and power-line impedance. A properly designed coupling circuit can adapt the impedance level of a certain signal to a chosen typical impedance level of the power line and subsequently be used as a bi-directional coupler for two-way communication.

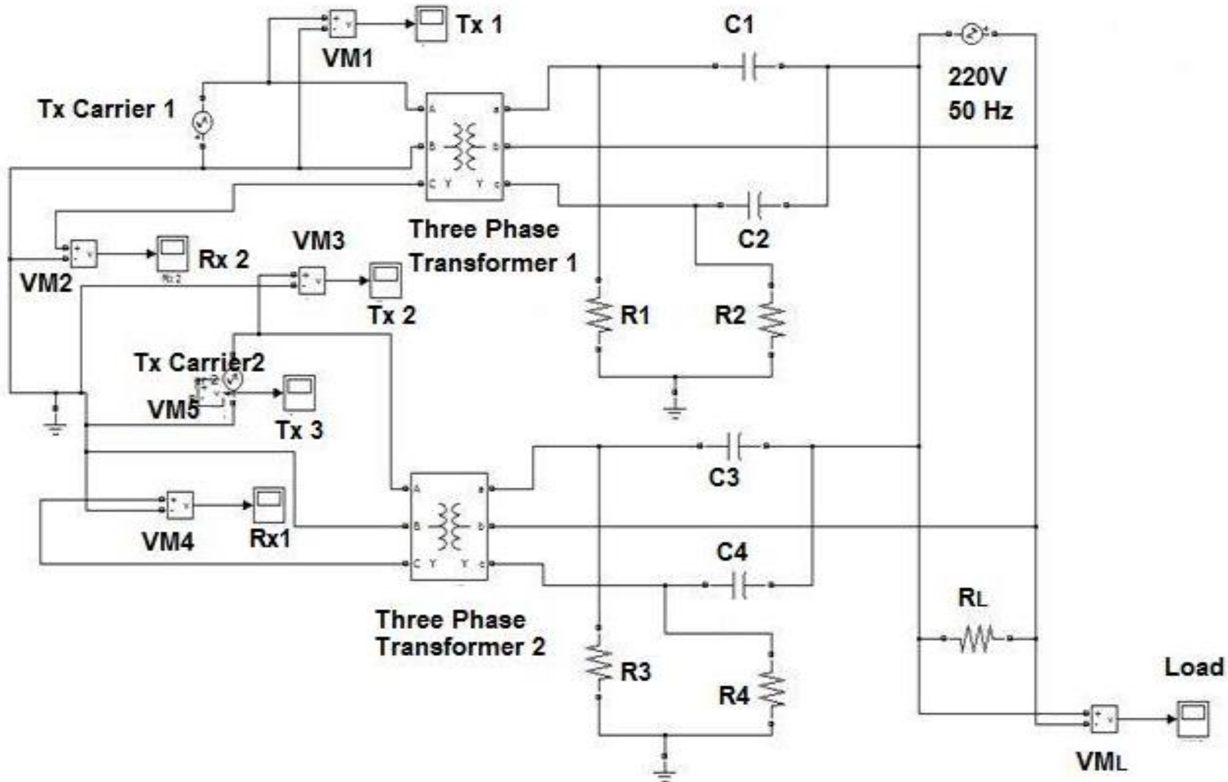

Fig 3.13: Overall simplified PLC circuit

Simulation output:

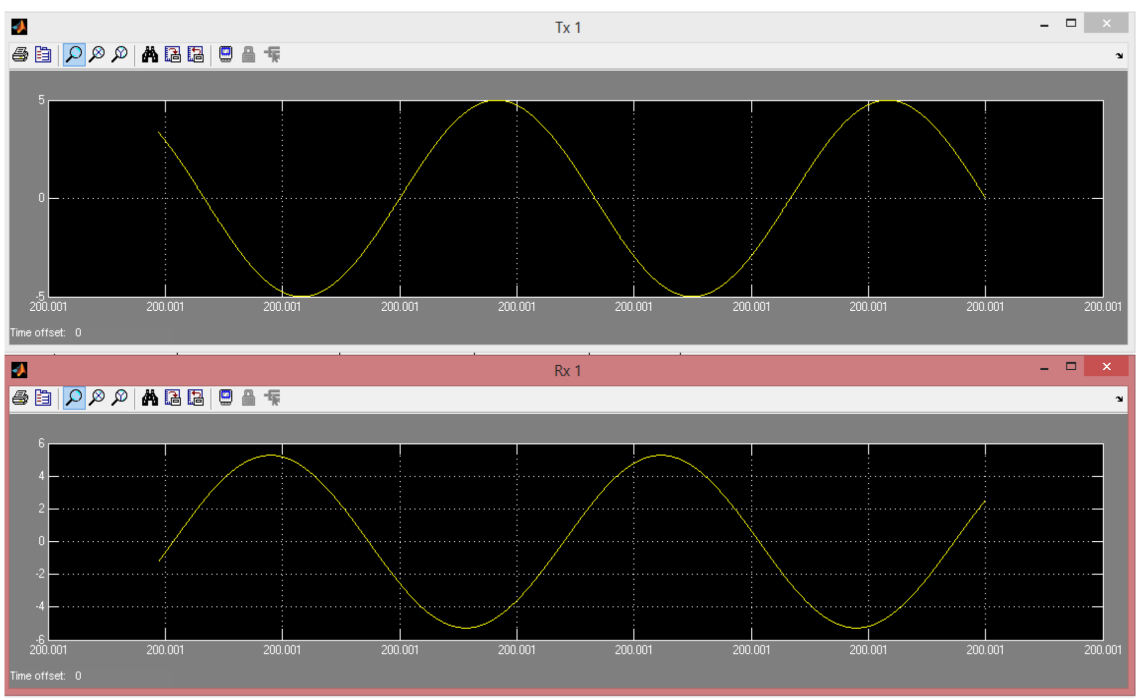

Fig 3.14: Simulation result of the simplified PLC circuit

Chapter 4: Result, Discussions and possible future works

4.1 Summary of Result

The main goal was to establish an analytical model of a power line communication system and verify the transit-receive capability. In order to do so several experimentations have been performed including both simulation and practical based work. In this section, a wrapped up version of total work has been presented.

Noise, attenuation, fading and multipath propagation are the main barriers of power line communication. Their details and possible methods of mitigating this barriers have been discussed in chapter 2. When the PLC signals are severely attenuated, the noise becomes a significant concern for data reception.

The types of noise discussed before are:

- Colored Background Noise
- Narrow band noise
- Periodic impulsive noise
- Periodic impulsive noise
- Asynchronous impulsive noise

Collective noise is the sum of all the noise types mentioned above.

Signals get attenuated with distance. A brief method of determining the attenuation of signal is shown in attenuation section of chapter 2. Also attenuation varies from area to area.

The power line channel has similarities with wireless channels. So different distribution functions such as Gaussian, Rician, Rayleigh, Nakagami-m etc. are also considered in power line communication channel model designs, this functions are considered to battle fading effect in PLC.

Another concern to PLC is multipath propagation which is connected to fading. Due to multipath propagation, the amplitude and phase of signal randomly fluctuates. This results in multipath fading.

Impedance matching is another important fact in power line communication. A common analogy of impedance in electric circuit is shown in chapter 2. In case of practical application several methods can be used for impedance matching. Line trap circuit was used to do so.

Line traps are connected in series with HV transmission line. The main function of line traps is to provide a high impedance at the carrier frequency band while introducing negligible impedance to the power frequency. The high impedance limits the attenuation of the carrier signal within the power system by preventing the carrier signal from being:

- → Dissipated at loads.
- → Grounded in the event of a fault outside the carrier transmission path.
- → Dissipated in the branch of main transmission path.

Several modulation techniques are available for power line communication. Both single carrier (ASK, FSK etc.) and multi carrier modulations are used. But current circumstance says that multi carrier OFDM technique is more suitable in power line environment. It has several advantages over other techniques when it comes to power lines.

High-speed power line communication systems usually employ multi-carrier modulations (such as OFDM or Wavelet OFDM) to avoid the intersymbol interference that multipath propagation would cause.

OFDM provides somewhat resistance to multipath propagation and it suits well at extreme conditions of a power line, loss is mitigated as well.

There are several noise channels present to counter noise (especially impulse noise).

Different types of noise modeling can be used such as,

- Asynchronous Impulsive Noise Modeling
- Cyclostationary Impulsive Noise Modeling
- Non-parametric impulsive noise estimation etc.

This models estimates the nature of noise and tries to counter it.

In chapter 3, a brief discussion on self-implemented designs was given. One special component used is ferrite core transformer. It provides high magnetic permeability and galvanic isolation which is essential in the circuit. Also it is very much effective in high frequencies than general transformers. It also provides low losses at high flux density and temperature as well as shows good stability at low condition.

The circuits have been tested with and without line traps. A simplified PLC circuit was provided that was also practically implemented. It provided with some interesting results. Several modulation schemes like ASK, FSK were tested on the circuit and both signals were successfully coupled with the power line using the bi directional coupler.

The Circuit can work as medium of various sorts of communication. ASCII codes can be sent by converting the signal from parallel to serial at the sending end to convert parallel data into bit stream and serial to parallel converter at the receiving end to use it. Many such applications can be performed such as home automations, regulations etc.

4.2 Work in progress and future works

In addition to establish an analytical model of a power line communication system and verify the transit-receive capability currently a work on Analysis of Attenuation Factor and Different Parameters in Power line Channel for A Multipath Signal Propagation Model is also undergoing.

4.2.1 Power Line Channel Model

The multi-path model views the channel as an unknown function that needs to be estimated based on training data; hence, it does not use any prior information such as the network topology or component connections. Instead, it proposes a parametric model of the channel frequency response based on TL theory. This modeling approach is useful when the network topology is not available or an ad hoc deployment is desired. It is based on the superposition of signal reflections at various loads predicted by TL theory. Its parametric form is given by

$$H(f) = \sum_{i=1}^{L} g_i \, e^{-(a_0+a_1 f^k)d_i} e^{-j2\pi f\tau_i} \tag{33}$$

The above transfer function is for broadband power line in the frequency range of 0.3 to 100MHz where,

L=No. of path;

g_i =Weighting factor for path i (less than 1);

a_0 & a_1= attenuation parameter;

f = frequency in Hz;

k=Exponent of attenuation factor (0.5 to 1);

d_i = Length of i-th path; τ_i = delay of i-th path.

4.2.2 Simulation

The above equation (33) has been simulated by MATLAB. Here it is observed that with the changing values of amplitude of transfer function changes significantly.

At first in fig 4.1, taking the fixed value a_1=1.0000005 and a_0=0.0000001, k is varied from 0.6 to 1. It is observed that with the increase of k, the corresponding amplitude of transfer function increases proportionally.

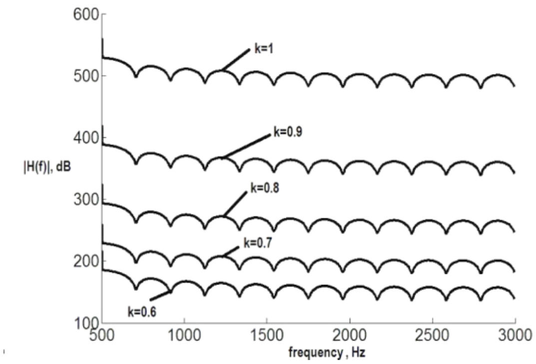

Fig 4.1: H (f) vs. frequency with varying ‘k’

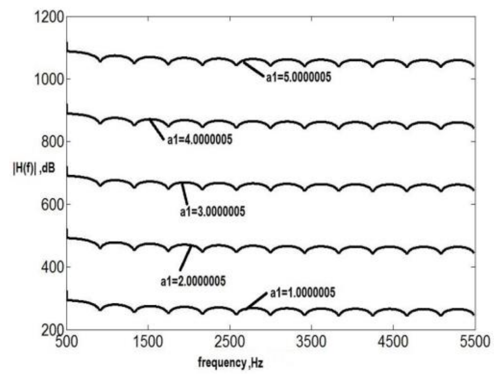

Fig 4.2: H (f) vs. frequency with varying a_1

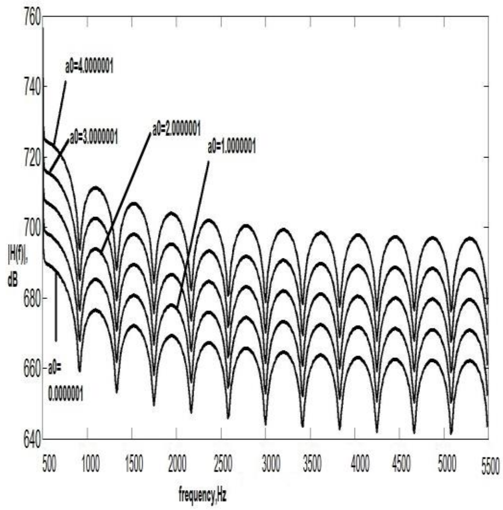

Fig 4.3: H (f) vs. frequency with varying a_0

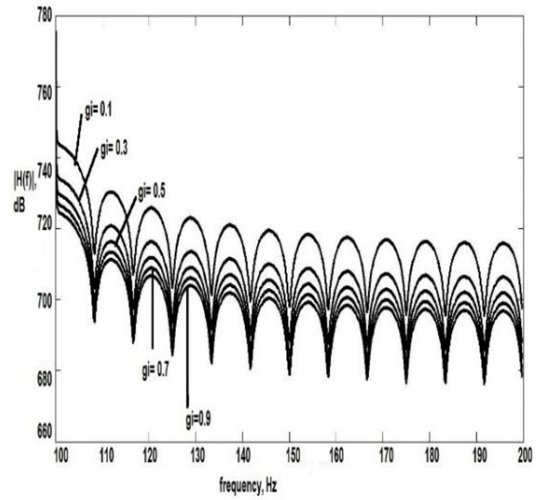

Fig 4.4: H (f) vs. frequency with varying g_i

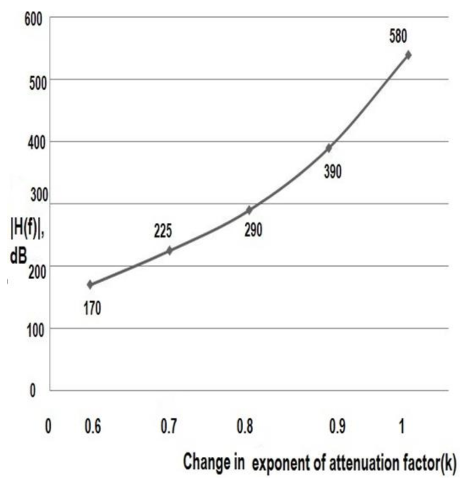

Fig 4.5: Improvement Curve against 'k'

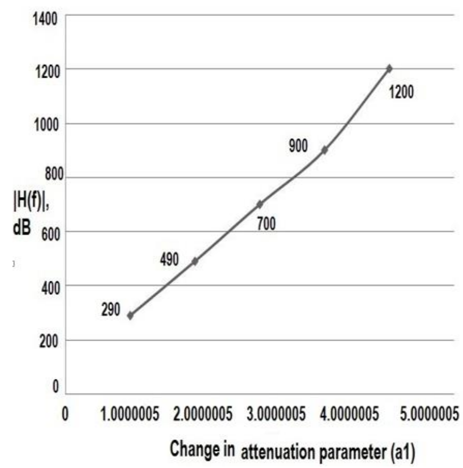

Fig 4.6: Improvement Curve against 'a_1'

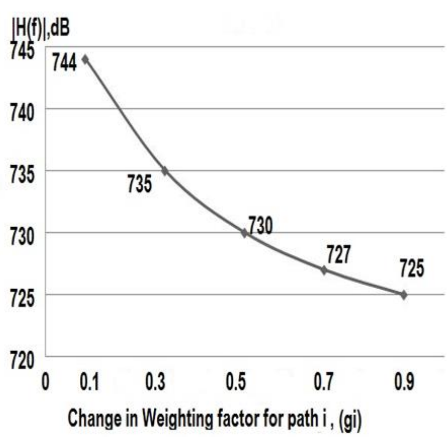

Fig 4.7: Performance Curve against 'g_i'

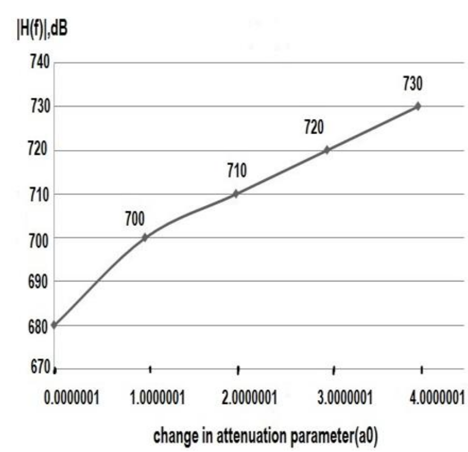

Fig 4.8: Improvement Curve against 'a_0'

Similarly, in Fig 4.3, the value of a_0 is increased from 0.0000001 to 4.0000001 and kept a_1 and k fixed. Consequently, it is observed that the amplitude of transfer function rises proportionally with the rising value of a_0. In Fig 4.4, the value of weighting factor, g_i is varied from 0.1 to 0.9 keeping the other parameters constant and it is observed that the change of |H (f)| is inversely proportional to with the change in g_i .

The magnitude of transfer function for different values of exponent of the attenuation factor k, attenuation parameters a_0 and a_1 and different values of weighting factors of i-th path , g_i have been compared. For different values of k, a_0, a_1 and g_i, the magnitude changes significantly. For example, when k=0.6, |H(f)|= 170 and when k=1, |H(f)|= 540. Again, for a_1=1.0000005, |H(f)|= 290 and for a_1=5.0000005, |H(f)|=1200. Similarly, at the value of a_0=0.0000001, |H(f)|= 680 and at a_0= 4.00000001, |H(f)|=730. Again, when g_i =0.1, |H(f)|= 744 and when g_i = 0.9, |H(f)|= 725. The data clearly indicates that the value of k, a_0 , a_1 and g_i play very important role in the improvement of transfer characteristics of power line communication. With the gradual increase of the attenuation factor and parameters, a better performance model is found as the amplitude of transfer function increases proportionally with these parameters. On the contrary, the change of magnitude of transfer function is inversely proportional to the change of weighting factor of i-th path.

In Fig 4.5, the improvement curve of H(f) with the change of 'k' has been shown. The curve clearly indicates almost the linear increase in the value of |H(f)| with the rise of 'k'. Similarly, in fig 4.6, 4.7 and 4.8 the improvement curves of |H(f)| against the value of 'a_1' , 'a_0' and 'g_i' are shown.

4.2.3 Matlab Code Used For Simulation

```
%clc;
%clear all;
%close all;
a0=0.0000001;
a1=1.0000005;
gi=.9;
k=0.7;
```

```
di=1:100;
ti=10^(-9);
f=50:100:9950;

for n=1:100
   y(n)=gi*(exp(-(a0+a1*(f(n)^k))*(di(n))))*exp(-
(j*2*pi*f(n)*ti));

end
p=5001:6000
length(y)
z=y+y+y
freqz(p,z)
hold on
```

4.2.4 Future Works

An attempt to develop a circuit design which can work as a medium to transfer various types of data using existing power line wires was taken. In order to do so several experimentations on some new methods like using ferrite core transformers, line traps in the PLC were practiced and some interesting results were found. This has provides with new opportunities for further developing the model. For example the model can be modified to carry ASCII codes to send character data, develop various home automation system etc. Even though almost all of them have been developed earlier, the main outcome of the research could be finding a simpler and cheaper way to develop a good, high quality PLC device (i.e. Modem) and spreading the research and use of PLC technology to a great extent. This could open new topic of research as we advance with our work. It can be hoped that the research work will be able to provide a good contribution and representation of significant research topics in the field of PLC.

An attempt to find a method for improvement of the magnitude of transfer function with the changing value of exponent of the attenuation factor, attenuation parameters and weighting factor of i-th path was taken. The proposed coupler is well suited for transmitting high frequency communication signals. Impedance mismatching problem between the coupler impedance and power line impedance is also solved using line trap circuit. This coupler can be effectively used for broad band communication in domestic as well as distribution power networks.

Finally, the transfer function for a power line communication model can be easily improved by changing its parameters which will help to design better quality model that will show low noise and attenuation factor in future.

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