Abstract

The purpose of this project is to determine the performance of a Power line communication connection by measuring its propagation characteristics.

For power line communication to become efficient, a model of their behaviour at frequencies from 0 to 30 MHz is required. The attenuation and phase response are of particular interest. In this project, indoor cables within a building were utilized. A three core indoor cable is modeled as a two wire lumped-element model with distributed parameters. These parameters are capacitance, inductance, conductance and resistance.

The predicted results, generated by MATLAB software closely matched those obtained by the measurements carried out on the 10m flat cable. The model and its results will allow communication designers to determine the optimal communication scheme for this power line channel.

However, more investigation is required to determine noise characteristics and impedance mismatch in the power line network before it can be completely modeled.

Dedication

This project is dedicated to the almighty God who has made it possible, and to my dear mother Mrs Chinwe Osuno who is my symbol of excellence and to my late father Mr. Chris Osuno who shines down from heaven like a star.

Acknowledgement

I want to thank God for sustaining and inspiring me through out this project. He is my Sovereign.

My most hearty thanks go to my Supervisors; Dr. Jim Gilbert and Mr. Nick Riley who encouraged and counseled me constantly. Thank you for bringing out the best in me.

I want to thank my lovely mother, who is my standard for excellence, my mentor, my teacher and my friend. Thank you for constantly praying for me.

I thank Loy, who assisted me with my laboratory measurements. May God reward you greatly.

I want to also thank my sister, Miss Ginika Osuno and my brother, Mr. Kene Osuno who were constantly concerned and supportive of my work. May God bless you beyond measure.

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Chapter 1

Introduction

In the last years, there has been a growing interest towards the possibility of exploiting power lines as an effective transmission means. Low voltage (LV) and medium voltage (MV) power lines are appealing because they provide a potentially convenient and inexpensive communication medium for control signaling and data communication. High voltage (HV) power lines can also be used for communication purposes, for example, in scenarios not covered by wired or wireless telecommunication infrastructures.

However, with the emergence of modern technologies including broadband, there is more than ever a need for the utility and service providers to discover solutions that are able to deliver the services to consumers at maximum performance. Only recently, companies have put serious attention to communicate over power lines for data networking.

The communication flow of today is very high. Many applications are operating at high speed and a fixed connection is often preferred. If the power utilities could make supply communication over a power-line to the customers, it could make a tremendous break-through in communications. Every household would be connected at any time and services being provided at real-time. Using power-line as a communication medium could also be a cost-effective way compared to other systems because it uses an existing infrastructure, wires exist to every household connected to the power-line network.

The deregulated market has forced the power utilities to explore new markets to find new business opportunities, which have increased the research in power-line communications in the last decade. The research has initially been focused on providing services related to the power distribution such as load control, meter reading, tariff control, remote control and smart homes. These value-added services would open up new markets for the power utilities and hence increase the profit. The moderate demands of these applications make it easier to obtain reliable communication. Firstly, the information bit rate is low; secondly, they do not require real-time performance (Selander, 1999).

Furthermore, the use of internet has increased in the past years. If it would be possible to supply this kind of network communication over the power-line, the utilities could also become communication providers, a speedily growing market. In contrast to power related applications, network communications require very high bit rates and in some cases real time responses are needed (such as video and TV). This complicates the design of a communication system but has been the focus of many researchers during the last years (Selander, 1999). Systems under trial exist today that claim a bit rate of 1 Mb/s, but most commercially available systems use low bit rates, about 10 – 100 Kb/s, and provides low-demanding services such as meter reading.

The power-line was initially designed to distribute power in an efficient way, hence it is not adapted for communication and advanced communication methods are needed. Today's research is mainly focused on increasing the bit rate to support high-speed network applications.

1.1 Objectives

The aim of this project is to find ways of measuring the performance of a Power line communication connection by measuring phase and attenuation characteristics.

In order to accomplish the stated aim, a series of objectives for this project were designed. This project is divided into 2 parts (part one and part two) according to the progress of the project. These objectives are as follows:

Part One

- Study and understand the functionality of Power Line Communication System.
- Examine the transmission line model.

Part Two

- Measure the characteristics of a power-line system.
- Model a Transmission line using MATLAB codes.

- Determine whether the model can predict power line behavior such as phase response and attenuation response to a certain degree of accuracy.

1.2 Project Organization

Although there were some changes in the objectives, the project was handled fairly and smoothly. In the first part, all necessary research and ground work was completed. After gaining a sound understanding of power-line communications and the scope of the project, it became easy to carry out some experiments and, start working towards our final objectives in the second part.

Chapter 2

Literature Review

This review is geared to give an in-depth understanding of power-line communication as a communication medium. It begins with a brief history of PLC, an overview of PLC and basic findings in this field of study.

2.1 History of Power Line Communication (PLC)

According to Brown (1999), the idea of utilizing power for communication is a very old invention. In 1838, the first remote electricity supply metering for the purpose of checking the voltage levels of batteries at an unmanned site in the London-Liverpool telegraph system was proposed by Edward Davy (Fahie, 1883).

In 1920, the carrier frequency transmission of voice over high voltage (HV) power lines was introduced. Carrier transmission over power lines (CTP) was of importance because of management and monitoring tasks and on the other hand, at the beginning of electrification, there was no full-coverage telephone network available. The applied frequencies for CTP were 15-500 KHz, the lower frequency being limited because of the cost for coupling equipment. The size of the coupling capacitor for HV can be seen in Fig 2.1.

From 1930 upwards, ripple carrier signaling (RCS) was became practical in the medium voltage (MV) and low voltage (LV) networks. The main tasks were to load distribution including the avoidance of extreme load peaks and smoothing of the load curves. In contrast to HV overhead lines, MV and LV networks were a poor medium because of a large number of branches.

Fig 2.1 Coupling capacitors in the HV distribution network [figure abstracted from Kosonen, 2008].

In the mid-1980’s, some experiments were carried out to analyze electric grid and its properties as data transfer medium on higher frequencies. The noise levels were also checked within the frequency range of 5 Hz to 500 KHz.

In the late 1980’s and early 1990’s, the development of bi-directional communication took place. The difference between technology used in those days and nowadays is that high frequencies are used now on the power grid network.

2.2 Overview of PLC

Powerline Communication (PLC) is a technology that employs the infrastructure of electrical power distributed system as a communication medium (Dostert, 1997). The power-line network is a large infrastructure covering most parts of the settled areas. Power-line communication can also be defined as a communication network based on electrical signals, carrying information, propagating over the power-line.

PLC refers to the concept of transmitting electrical power distribution network as a communication channel. A communication *channel* is defined as the physical path between two communication nodes on which the communication signal is propagated (Andersson, 1998). In a low-voltage grid, there are a lot of different channels; in fact the links between a sub-station and each household are all different channels with different characteristics and qualities.

The quality is estimated from how good the communication is on a channel. The quality is mostly a parameter of the *noise level* at the receiver and the *attenuation* of the electric signal at different frequencies. The higher the noise level, the harder it is to detect the received signal. If the signal gets attenuated on its way to the receiver, it could also make the decision harder because the signal gets more hidden by noise (Kosonen, 2008).

On the power-line, the noise is generated from all loads to the grid. Also broadcast radio interferes with the communication. The attenuation is a parameter of the physical length of the channel and impedance mismatches in the grid. The power-line is often considered a harsh environment because of the time-variant characteristics of the noise and attenuation, but this is also the case in most communication systems and only limits the performance that can be achieved. Advanced communication systems exists today, designed to overcome the problems with such channels as, e.g., GSM.

Furthermore, the PLC technology allows a flow of information through the same cabling that supplies electrical power. This novel idea of communication helps in bridging the gap existing between the electrical and communication network. PLC technology could provide the consumer with a spectrum of services such as internet, home entertainment, and home automation and enable the electricity supply authority to efficiently manage their distribution networks in a competitive manner (Pasupathy, 1995).

PLC systems consists of terminal devices that are plugged into or attatched to the electrical power supply network and allow data to be transmitted through the network to other terminal devices plugged into or attatched to the network (ACA, 2003). The use of the existing electrical power supply network wiring reduces costs and provides convenient access to broadband interconnection between devices.

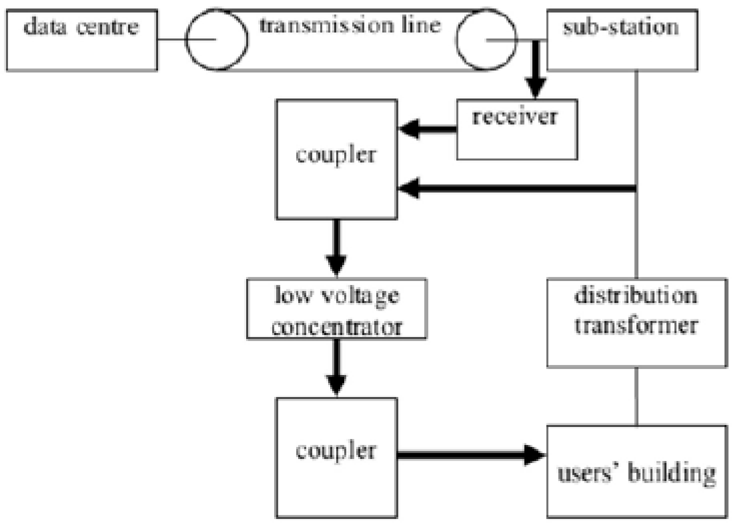

Fig.2.2 A simple PLC system (figure abstracted from Biswas, 2008).

This technique has immediate attraction for meter communication system, since every consumer is connected to the communication network and that network is owned and controlled by the electrical supply authority. In a meter-reading communication system, high-power signals are transmitted through the network, which are then received by all connected meters. The system has been extensively implemented in Europe and especially in France (Dural, 1997).

PLC systems can also be used to transfer data inside buildings using power lines discounting the cost of insulating communication cables. A recent survey shows that one-third of new broadband customers will choose power line communication by 2012 (Dostert, 1997). PLC technology could also let the power distribution companies open lucrative revenue streams by bundling electricity supply with broadband telecommunication access providing high speed and reliable communication traffic including internet access (Waldec et al., 1998).

2.3 Power Supply Networks

The electrical supply systems consist of three network levels that can be used as a transmission medium for the realization of PLC networks (as shown in Fig. 2.1):

- **High Voltage (110-380KV) networks**: These networks connect the power station with large supply regions or huge customers. They usually span very long distances, allowing power exchange within a continent. High voltage networks are usually realized with overhead supply cables.
- **Medium Voltage (10-30KV) networks**: These networks supply larger areas, cities and big industrial or commercial customers. The spanned distances are significantly shorter than in the high voltage networks. The medium voltage networks are realized as both overhead and underground networks.
- **Low Voltage (230/440V) networks**: These networks supply the end user either as individual customers or as single users of a big customer. Their length is usually up to a few hundred meters. In urban areas, low voltage networks are realized with underground cables, whereas in rural areas, they exist usually as overhead networks. It is 110V in USA.

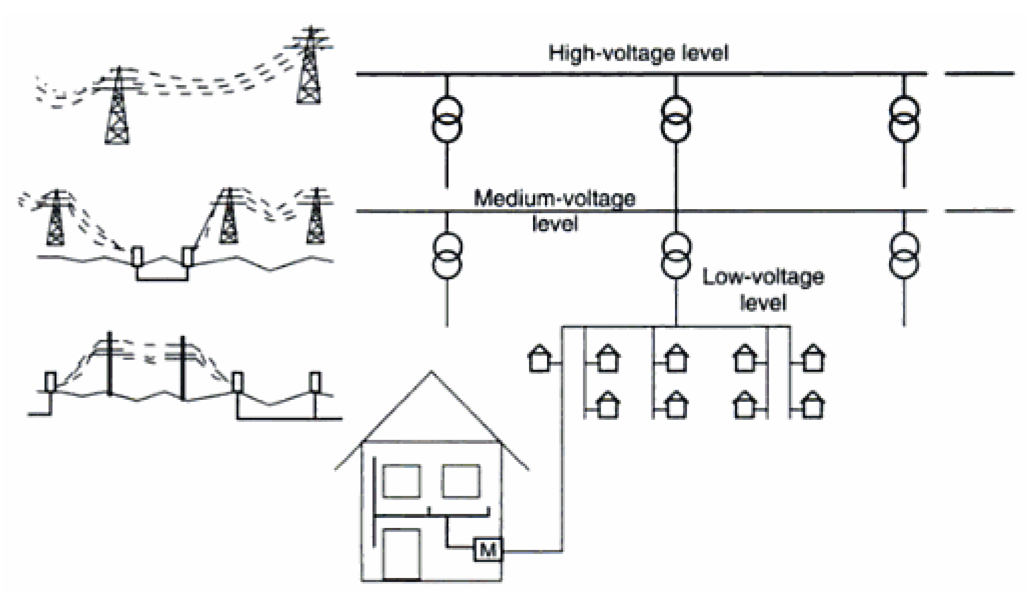

Fig 2.3 Structure of electrical supply networks (Figure abstracted from Hrasnica et al., 2004).

2.4 Standards

The communications over the electrical power supply networks is specified in a European standard CENELEC EN 50065, providing a frequency spectrum from 9 to 140 KHz for powerline communications. CENELEC norm significantly differs from America and Japanese standards, which specify a frequency range up to 500 KHz for the application of PLC services.

Band	Frequency range (kHz)	Max. transmission amplitude (V)	User dedication
A	9–95	10	Utilities
B	95–125	1.2	Home
C	125–140	1.2	Home

Fig. 2.4 CENELEC bands for powerline communications (Figure abstracted from Hrasnica et al., 2004).

CENELEC norm makes possible data rates up to several thousand bits per second, which are sufficient only for some metering functions, data transmission with very low bit rates and the realization of few numbers of transmission channels for voice connections. However, for application in modern telecommunications networks, PLC systems have to provide much higher data rates (beyond 2Mbps).

For the realization of higher data rates, PC transmission systems have to operate in a wider frequency spectrum (up to 30MHz). However, there are no PLC standards that specify the operation of PLC systems out of the frequency bands defined by CENELEC norm. Currently, there are several bodies that try to lead the way for standardization of broadband PLC networks, such as the following:

- **PLCforum:** It is an international organization with the aim to unify and represent the interests of players engaged in PLC from all over the world. There are more than 50 members in the PLCforum which include manufacturer companies, electrical supply utilities, network providers, research organizations and a host of others. PLCforum is organized into four working groups: Technology, Regulatory, Marketing and Inhouse working group.

- **HomePlug Powerline Alliance**: Its purpose is to provide a forum for the creation of open specifications for high-speed home powerline networking products and services. HomePlug is concentrated on in-home PLC solutions and it works close to PLCforum as well.

2.5 Advantages and Disadvantages of PLC

PLC technology offers many advantages over other wired and wireless communication technology that makes it efficient and economic to use in some applications. PLC integrates the transmission of communication signal and power signal through the same electrical power cable. The major benefit is the union of two important applications on a single system. The data link appears “transparent” to the user. Although the devices are connected through the powerline, consumers perceive that there is a “separated” link available for data communications. Also, PLC uses the existing infrastructure of powerline networks which means a great savings in wiring. Furthermore, PLC is more secure than wireless and telephone line communication. Transmitted data within any house or company cannot be hacked by anyone out of the sub-network. Also, with the technical advancements, PLC is capable of distributing data at 14Mbps speed and future data transmission rates are predicted at 100Mbps, making it a cutting edge technology of the future. In addition, with respect to distribution of multimedia, PLC is capable of distributing audio, video and other real time services alongside data, throughout the home.

On the other hand, there are some difficulties and disadvantages that hinder using PLC as a universal communication system. In addition to the interference problem created from the radiation from power lines, PLC systems suffer from the noise created by loads and devices connected to the power line network which imposes restrictions on the available bandwidth (Al-Zobi et al., 2008). Also, irregularities in some international markets are also preventing the development of global standard for distributing data over existing power line systems. Moreover, in comparison to the phone line network equipment, the power line networking modules are more costly and this also needs addressing to make power line a preferred technology for networking. Since the powerline was devised for transmission of power, the use of this medium for data transmission (especially at high frequencies) presents some technically challenging problems.

Powerline networks are usually made of a variety of conductor types and cross sections joined almost at random. Therefore a wide variety of characteristic impedances are encountered in the network. This imposes interesting difficulties in designing the filters for these communication networks.

2.6 Attenuation in PLC Systems.

Attenuation can be defined as the loss of signal strength as the signal propagates over a certain distance. For a transmission line, the input impedance relies on the type of line, its length and the termination at the end. The characteristic impedance of a transmission line, Z_o is the impedance measured at the input of this line when its length is infinite. Under these conditions, the type of termination at the far end has no effect (Dostert, 1997). A standard distributed parameter model can obtain the characteristic impedance of an unloaded power cable, and it can be mathematically represented as:

$$Z = \sqrt{(R + jwL)/(G + jwC)}$$

At the frequencies of interest for PLC communications (the high frequency range), this can be approximated to:

$$Z = \sqrt{(L/C)}$$

where L and C are the line impedance and capacitance per length.

High frequency signals can be inserted on to the power line by using an appropriately designed high pass filter. Maximum signal power will be received when the impedance of the transmitter, power line and the receiver are all matched. Power line networks are usually made of a variety of conductor types and cross sections joined almost at random. Therefore a wide variety of characteristic impedances are encountered in the network. Unfortunately, a uniform distributed line is not a suitable model for PLC communications, since the power line has a number of loads (appliances) of differing impedances connected to it for variable amounts of time. Channel impedance is a strongly fluctuating variable that is difficult to predict. The overall impedance of the low voltage network results from a parallel connection of all network's loads, so the small impedances will play a dominant role in determining overall impedance. Overall network impedances are not easy to predict either (Hrasnica et al., 2004).

The most typical coaxial cable impedances used are 50 and 75-ohm coaxial cables. A twisted pair of gauge-22 wire with reasonable insulation on the wires measures at about 120 ohms. Clearly, channel impedance is low. This presents significant challenges when designing a coupling network for PLC communications. Maximum power transfer theory states that the transmitter and channel impedance must be matched for maximum power transfer. With strongly varying channel impedance, this is tough. We need to design the transmitter and receiver with sufficiently low output/input impedance in the majority of expected situations.

2.7 Noise and Cable characteristics in PLC

Noise environment of a PLC network is very complex (Jung, 2002). The major source of noise on power line are from electrical appliances, which utilize the 50 Hz electric supplies and generate noise components, which extend well into the high frequency spectrum. Apart from these induced radio frequency signals from broadcast, commercial, military, citizen band and amateur stations severely impair certain frequency bands on power line. The primary sources of noise in residential environments are universal motors, light dimmers and televisions. This noise can be classified into 6 categories:

- Coloured background noise.

- Single-event impulse noise.
- Periodic impulsive noise.
- 50 Hz Periodic noise.
- Asynchronous impulsive noise.
- Continuous impulsive noise.

2.7.1 50 Hz Periodic Noise

Noise synchronous to the sinusoidal power line carrier can be found on the line. The sources of this noise tend to be silicon-controlled rectifiers (SCRs) that switch when the power crosses a certain value, placing a voltage spike on the line. This category of noise has line spectra at multiples of 50 Hz.

2.7.2 Single-event impulse noise

This category includes spikes placed on the line by single events, such as a lightning strike or a light-switch turn on or off. Capacitor banks switched in and out create impulse noise.

2.7.3 Periodic impulsive noise

The most common impulse noise sources are triac-controlled light dimmers. These devices introduce noise as they connect the lamp to the AC line partway through each AC cycle. These impulses occur at twice the AC line frequency as this process is repeated every half-AC cycle.

2.7.4 Continuous impulsive noise

This kind of noise is produced by a variety of series-wound AC motors. This type of motor is found in devices such as found in vacuum cleaners, drillers, electric shavers and many common kitchen appliances. Commutator arcing from these motors produces impulses at repetition rates in the several kilohertz range. Continuous impulsive noise is the most severe of all the noise sources.

2.7.5 Asynchronous periodic noise

This type of noise has line spectra uncorrelated with 50 Hz sinusoidal carriers. Television sets generate noise synchronous to their 15374 Hz horizontal scanning frequency. Multiples of this frequency must be avoided when designing a communications transceiver. It was found that noise levels in a closed residential environment fluctuate greatly as measured from different locations in the building. Noise levels tend to decrease in power level as the frequency increases. In other words, spectrum density of power line noise tends to concentrate at lower frequencies. This implies that a communications carrier frequency would compete with less noise if its frequency were higher.

2.7.6 Coloured Background Noise

This is what every subscriber sees as already present on the line, and not caused by subscribers' appliances. Typically, this originates from the distribution transformer, public lighting systems and a host of others.

2.8 Findings

Among these, the coloured background noise and the asynchronous impulsive noise are the most important.

Liu et al (2004) made a sample of coloured background noise spectrum measured in their laboratory and it is shown in the Figure 4.1 below. They found out that the background noise is smoothly distributed over the spectrum. Its power spectral density is found to be a decreasing function of frequency, and on average, it is equal to:

$$N(f) = 10^{(a - b \cdot f^{c})} \text{ (W/Hz)} \qquad \text{-----------------} \quad (1)$$

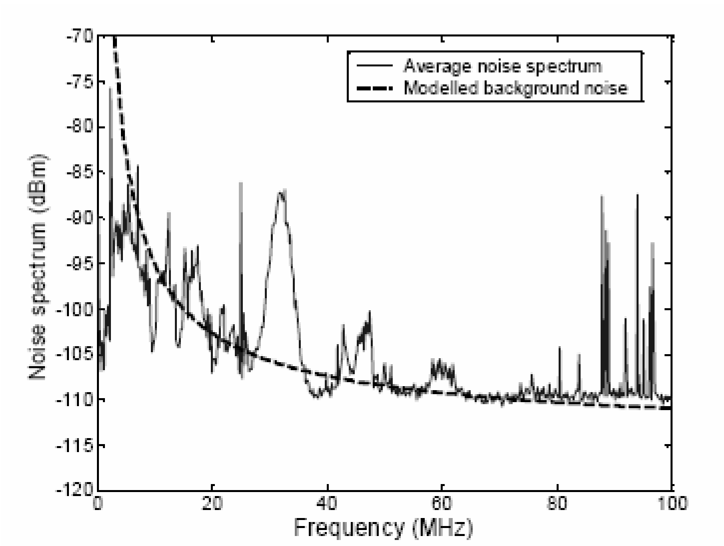

Figure 2.5 Background noise and its approximation [Figure abstracted from Liu et al., 2004].

By using polynomial curve fitting algorithm provided by MATLAB, they found that a = -115, b = 100 and c = -0.8 proved to be in a relatively good agreement with the measurement results as shown in the figure.

Asynchronous impulsive noise is caused by switching transients in the distribution network. The impulses have duration from some microseconds up to a few milliseconds.

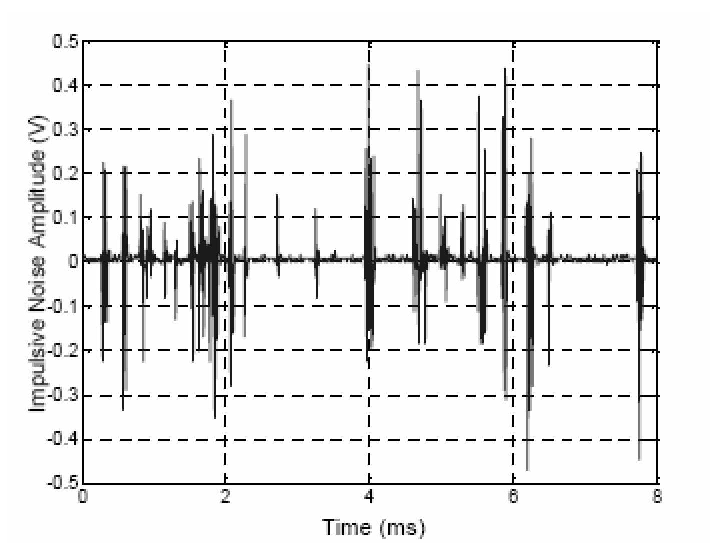

Figure 2.6 Asynchronous impulsive noise (in ms scale) [Figure abstracted from Liu et al., 2004].

The power spectral density of this type of noise, on average can have levels of 30dB above the background noise.

Coloured noise is usually present in low and medium voltage power line channels. The filter used for generation of coloured noise is a finite impulse response (FIR) complex filter with coefficients obtained using Cholesky factorization applied to the low pass filter coloured noise power spectrum (Haykin, 2001).

According to Pighi and Raheli (2007) besides frequency selectivity, the dominant channel disturbances occurring in power line channels in the frequency range between a few hundred KHz and 20MHz are coloured background noise, narrowband interference and impulse noise.

In this work, they presented the coloured noise power spectrum in a simple three-parameter model shown below:

$$S_{nc}(f) = a + b. |f|^{c} \text{ dBm/Hz} \text{ ------------------- (2).}$$

with a = -145, b = 53.23 and c = -0.337.

They concluded that this simple model allows us to capture the main characteristics of the coloured background noise, that is, the fact that the coloured noise power spectrum decreases as the frequency increases.

In contrast to this, Yu and Pasupathy (1995) insist that a realistic power spectrum may present some variations with respect to the power spectrum predicted by (2).

Cable characteristics are also very important in an efficient Power line connection. The type of the cable used and its size are very important parameters for setting-up a PLC connection.

Gulliet et al (2009) carried out an experiment to find out the influence of cable length on PLC systems. They used a cable composed of a global shield, making the interconductor distance constant. They carried out the experiment with three different cable lengths of 30 metres, 50 metres and 70 metres respectively.

The results for a 30 metre, 50 metre and 70 metre cable are presented in fig. 4.3

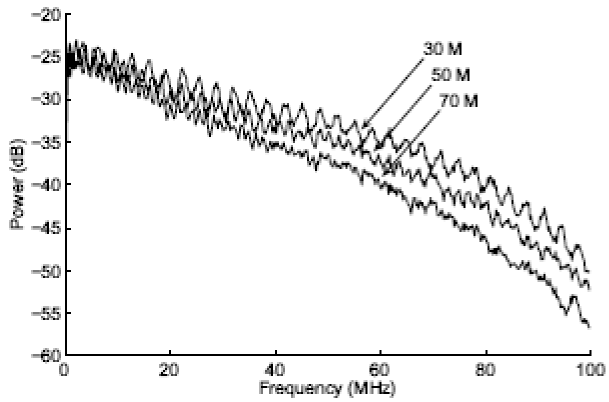

Fig. 2.7 Ripples in Bandwidth [figure abstracted from Gulliet et al., 2009].

The ripples in the bandwidth are caused by the line impedance mismatch. These reflected signals will be added to the measured signal by equation 3 below:

$$t_p = l/\upsilon_p \quad \text{and} \quad \upsilon_p = c/\sqrt{\epsilon_r} \quad \text{-------------} \quad (3)$$

where l is the length of the cable, υ_p is the propagation speed, $c \approx 3 \times 108$ m/s is the light speed in the vacuum and ϵ_r is the permittivity of the dielectric.

Therefore, I can say that the measurement enables the cable propagation time and dielectric permittivity to be evaluated using (3).

The measurement system for indoor shortwave powerline noise is shown in Fig. 4.4 below:

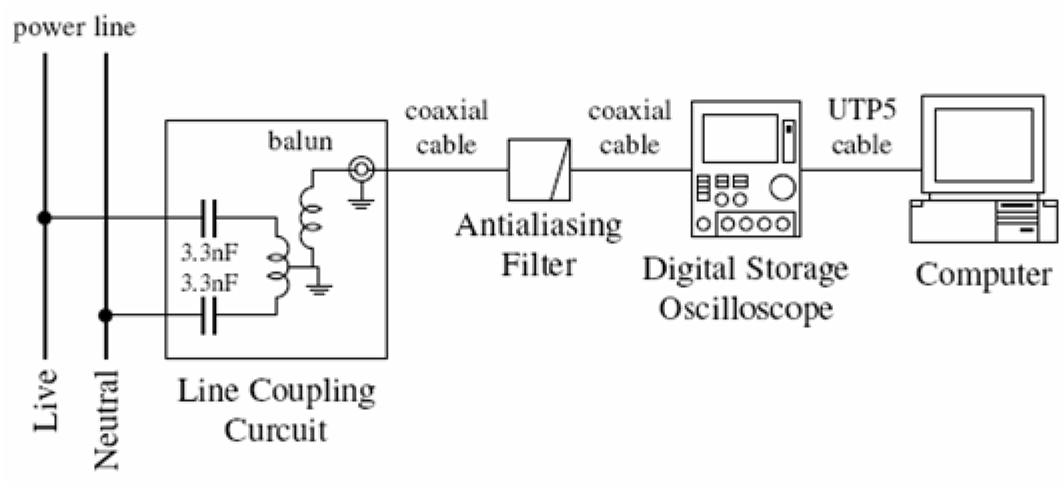

Fig. 2.8 System for measuring power line noise [Figure abstracted from Umehara et al., 2006].

It consists of the power-line connected to a coupling circuit (which has capacitors connected in series). A filter and oscilloscope are also present in the system. The filter is used to restrict the bandwidth of a signal to satisfy the Nyquist sampling theorem.

Zimmermann and Dostert (2002) used the system above to measure power line noise. They detected impulses from the measured noise by using the chi-squared test and modeled impulse duration. They concluded that there is a consistency of static for impulse duration and impulse amplitude between the measured noise and the modeled noise.

In many measurement reports on power line noise, spectrum analyzers are often used to show average or peak values of power line noise in the frequency domain. Some reports focus on noise waveforms in the time domain, but only for a short time period.

In contrast to this, Katayama, Yamazato and Okada (2006) used measurement of the whole noise waveforms in a long observation time in their research. It is not exactly clear which one of these methods is better.

The measurement and parameter determination of noise waveforms at many locations, the construction of a database of power line noise and the establishment of a standard set of parameters represent important future areas of investigation.

Power-line noise can interfere with radio communications and broadcasting. Essentially, the power-lines are associated hardware generate unwanted radio signals. Power line noise can impact radio and TV deception and internet services.
Communication through power lines offers a broad field for investigation especially in the areas of how to reduce the effect of noise in the power line connection.

2.9 The Power-Line as a Communication Channel

The figure below shows a digital communication system using the power-line as a communication channel. The transmitter is shown to the left and the receiver to the right. Important parameters of the communication system are the output impedances, Z_t, of the transmitter and the input impedance, Z_l, of the receiver.

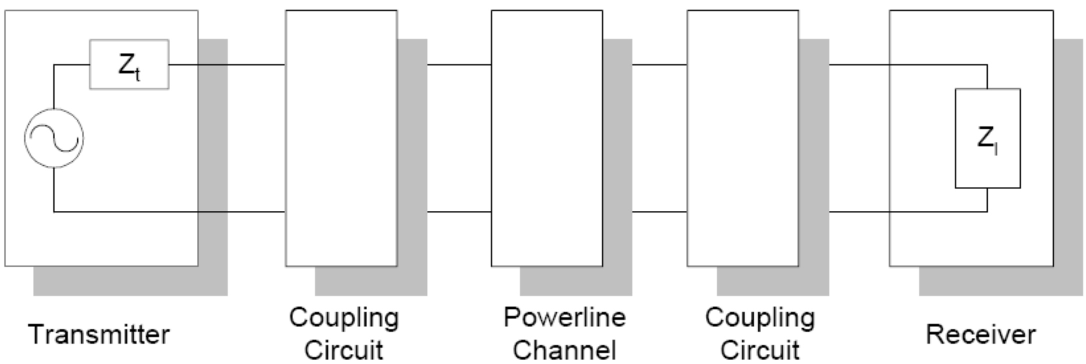

Fig. 2.9 A digital communications system for the power-line channel (figure abstracted from Dostert, 1997)

A coupling circuit is used to connect the communication system to the power-line. The purpose of the coupling circuits is two-fold. Firstly, it prevents the damaging 50Hz signal, used for power distribution, to enter the equipment. Secondly, it certifies that the major part of the received/transmitted signal is within the frequency band used for communication. This increases the dynamic range of the receiver and makes sure the transmitter introduces no interfering signals on the channel.

2.9.1 Bandwidth Limitations

In Europe, the allowed bandwidth is regulated by the CENELEC standard. The standard only allows frequencies between 3 kHz and 148.5 kHz (CENELEC, 1995). This puts a hard restriction on power-line communications and might not be enough to support high bit rate applications, such as real-time video, depending on the performance needed.

Figure 2.10 shows the bandwidth as specified by CENELEC standard. The frequency range is subdivided into five sub-bands. The first two bands (3-9 and 9-95 kHz) are limited to energy providers and the other three are limited to the customers of the energy providers. In addition to specifying the allowed bandwidth, the standard also limits the power output at the transmitter.

In order to increase the bit rate, larger bandwidth may be needed. Recent research has suggested the use of frequencies in the interval between 1 and 20 MHz (Fröroth, 1998). If this range could be used, it would make an enormous increase in bandwidth and would perhaps allow high bit rate applications on the power-line. An important problem is that parts of this frequency band is assigned to other communication system and must not be disturbed. Other communication systems using these frequencies might also disturb the communication on the power-line. Examples of communication systems in this interval are broadcast radio, amateur radio and airplane navigating.

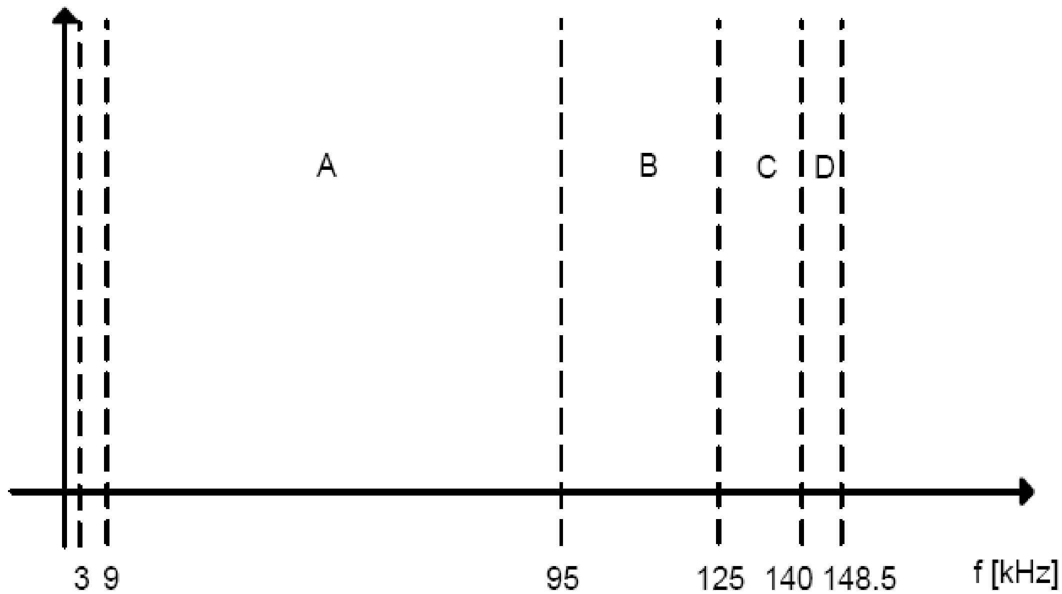

Fig. 2.10 The frequency bands in the CENELEC standard (Figure abstracted from CENELEC, 1995).

2.9.2 Radiation of the Transmitted Signal

When transmitting a signal on the power-line, the signal is radiated in air. One can think of the power-line as a huge antenna, receiving signals and transmitting signals. It is important that the signal radiated from the power-line does not interfere or impede with other communication systems.

When using the frequency interval 1-20 MHz for communication, the radiation is extremely important because many other radio applications are allocated in this frequency interval. It is not suitable for a system to interfere with, e.g., airplane navigation or broadcast systems. Recent research has studied this problem and tried to set up a maximum power level of transmission (Lauder and Sun, 1999). It is important that this work is finished in the near future since it limits the use of this bandwidth and the development of communication systems for the power-line channel.

When the cables are below the ground, the radiation is small. Instead, it is the radiation from the households that makes the major contribution. Wires inside households are not shielded and thus radiate heavily. A solution might be to use filters to block the communication signal from entering the household (Newbury, 1999).

2.9.3 Impedance Mismatches

Usually, at conventional communication, impedance matching is attempted, such as the use of 50 ohm cables and 50 ohm transceivers. The power-line network is not matched. The input (and output) impedance varies in time, with different loads and location. It can be as low as milli Ohms and as high as several thousand of Ohms and is especially low at the sub station (Nicholson and Mallack, 1973).

Except the access impedance, several other impedance mismatches might occur in the power-line channel. For instance, cable boxes do not match the cables and hence the signal gets attenuated.
Recent research has suggested the use of filters stabilizing the network (Newbury, 1999). The cost of these filters might be high and they must be installed in every household and perhaps also in every cable-box.

2.9.4 Signal-to-Noise-Ratio

A key parameter when estimating the performance of a communication system is the *signal-to-noise power ratio*, *SNR* (Proakis, 1995).
It can mathematically be represented below as:

$$SNR = \text{Received Power} / \text{Noise Power}$$

This parameter is related to the performance of a communication system. The higher the SNR the better the communication.

The noise power on the power-line is a sum of many different disturbances. Loads connected to the grid such as TV, Computers and vacuum cleaners generate noise propagating over the power-line. Other communication systems might also disturb the communication, thus introducing noise at the receiver.

When signal is propagating from the transmitter to the receiver, the signal gets attenuated. If the attenuation is very high, the received power gets very low and might not be detected. The attenuation on the power-line has shown to be very high (up to 100dB) and puts a restriction on the distance from the transmitter to the receiver (Dostert, 1998). An option might be to use repeaters in the cable-boxes, thus increasing the communication length.

The use of filters could improve the signal-to-noise ratio (Newbury, 1999). If a filter is placed at each household blocking the noise generated indoors from entering the grid, the noise level in the grid will decrease, but the cost is a higher complexity.

It is important to point out that although the power-line is considered a harsh environment when it comes to attenuation and disturbances, these parameters exists in any communication system used today.

2.9.5 The Time-variant Behaviour of the Grid

A problem with the power-line channel is the time-variance of the impairments. The noise level and the attenuation depend partly on the set of connected loads, which varies in time. A channel which is time-variant complicates the design of a communication system. At some time, the communication might work well but at other times a strong noise source could be inherent on the channel, thus blocking the communication.

To solve this, a possible solution is to let the communication system to adapt to the channel (Proakis, 1992). At any time, the characteristics of the channel are estimated, e.g., through measurements, and the effect is assessed to make a better decision. The cost of this is higher complexity.

2.9.6 A Channel Model of the PLC Channel

In the previous sections, we have seen some impairments that reduce the performance of a power-line system and they are:

- Impedance mismatches at the transmitter
- Channel attenuation
- Disturbances (noise)
- Impedance mismatches at the receiver
- Time-variations of the impairments

Figure 2.11 shows a model of the power-line channel with the parameters above. All impairments except noise are shown as time-variant linear filters characterized by its frequency response. The disturbance is shown as an additive interfering random process.

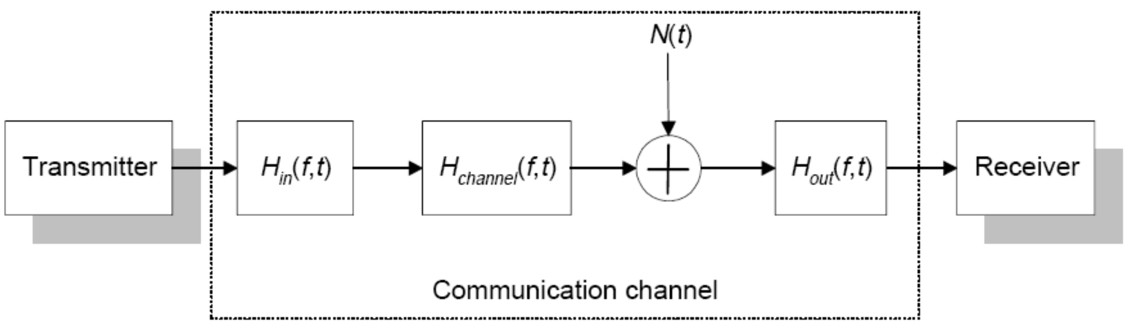

Fig. 2.11 Impairments present on the power-line channel (Figure abstracted from Dostert, 1997).

All the impairments above can be incorporated into a single filter model, shown in Figure 2.12, consisting of a time-variant filter and additive noise.

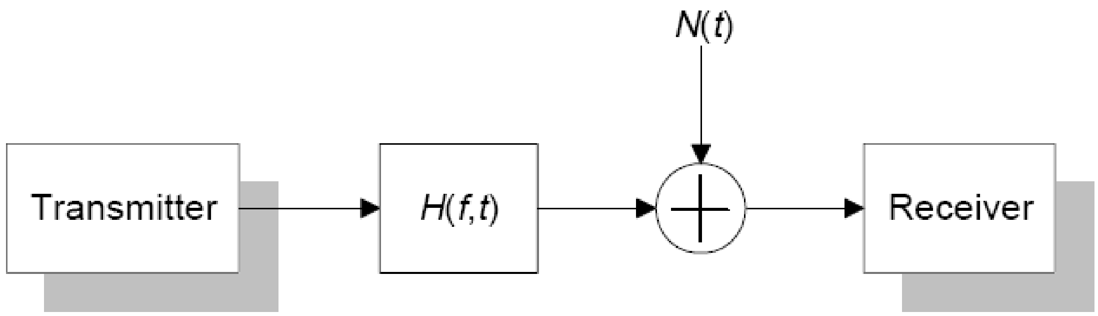

Figure 2.12 A simplified model of the power-line channel (Figure abstracted from Dostert, 1997)

Despite its simple form, this model captures a whole range of properties essential to communication system design and to the corresponding performance (Proakis, 1995).

In a nutshell, the transfer function and noise can either be estimated through measurements or derived by theoretical analysis. Measurements on the power-line channel and theoretical models can be found in a lot of research materials but a lot of measurements and modeling are still needed to get a thorough understanding of the network due to the inconsistency of the characteristics.

Chapter 3 Transmission Line Model

3.1 Indoor Power Line

Generally, there are two main types of cable that would be available within an indoor PLC network: flat TPS and circular cords. Circular cords are designed to be bendable and are used for interconnection between appliance and the wall sockets. TPS on the other hand are not as bendable and usually have a minimum bending radius (General Cables, 2004). TPS are usually used for wiring inside walls, between sockets. These cables all consists of three conductors which are: phase, neutral and earth. The New Zealand Electrical Code of Practice requires wiring for sockets and permanent connections to have a minimum conductor area of 1.5 mm^2 (Ministry of Commerce, 2004). This transmission line model will be based on a TPS cable. The dimensions of a common TPS cable are shown in Figure 3.2c below.

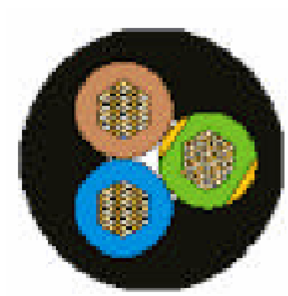

Figure 3.1 Cross Section of a Circular cord (figure abstracted from General cables, 2004).

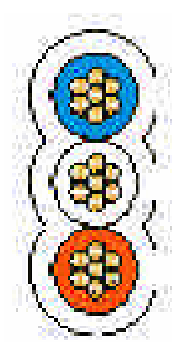

Figure 3.2 Cross section of a TPS Cable (figure abstracted from General cables, 2004).

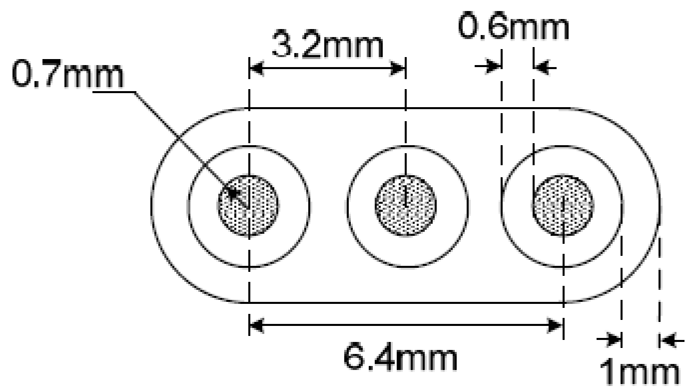

Figure 3.3 TPS Cable dimensions (figure abstracted from General cables, 2004)

Polyvinylchloride (PVC) is the most commonly used insulation material on these power cables. Although the properties of basic PVC are well documented, manufacturers add different additives to their PVC to enhance certain properties. These enhancements may include fire retardants, UV protection, increased flexibility or colour.

These additives however will alter the electrical properties of the PVC. Electrical permittivity and conductivity are two key factors that are often altered by these new additives. For the model to be accurate, experiments are needed to obtain fairly accurate values for these two properties.

3.2 Two-wire Transmission Line

The power lines can be treated as transmission lines. The transmission line is basically a two port network with two terminals at each end. These power lines operate in a transverse electromagnetic mode (TEM). In a TEM transmission line, the electric and magnetic fields are transverse to the direction of signal propagation. Other examples include coaxial cables and parallel plates (Ulaby, 2001).

Although real power lines are actually not made up of three wires, these indoor power cables can be approximated by a two-wire model since communication and data transfer would only occur on two or three conductors. The information would be sent through the phase and the neutral conductor. The earth conductor can not be used as it is always grounded and can not carry any information.

The phase and neutral conductors are located next to each other. This helps to minimize electromagnetic interference (EMI). If the two conductors on the outside were to be used, the electric and magnetic field generated by the broadband signal can create interference on the inside conductor.

New Zealand regulations also require that Multi Earth Neutral System (MENS) is implemented. In a MENS system, the earth and neutral conductors are connected together at the distribution transformer, at the main switchboard on every consumer's premises and at intermediate points (Ministry of Commerce, 2004). In theory, when MENS is operating, the potential difference between the earth and neutral conductors is zero and thus the three core cable can be approximated as a two core cable. However in practice, there are usually few milliamps on the earth conductor.

Another assumption made on the cables is that each line is considered as a single conductor. Normally each core is made up of a number of strands of copper wire twisted together to form a bundle. These can be from three strands in TPS to 28 strands in flexible three core cable (General cables, 2004). While this assumption makes the formulation of the model easier, the results generated can be considered as a worst case scenario, since having multiple strands will reduce the resistance at high frequencies.

3.3 Lumped Element Model

By using a lumped element model, various elements of the transmission line can be represented in an equivalent circuit. There are four basic elements to this equivalent circuit, all of which are per unit length units:

- R – Resistance of both conductors (Ω / m)
- G – Conductance of the insulating material used by the cable (S / m)

- L – Inductance of both conductors (H /m)
- C – Capacitance between the conductors (F / m)

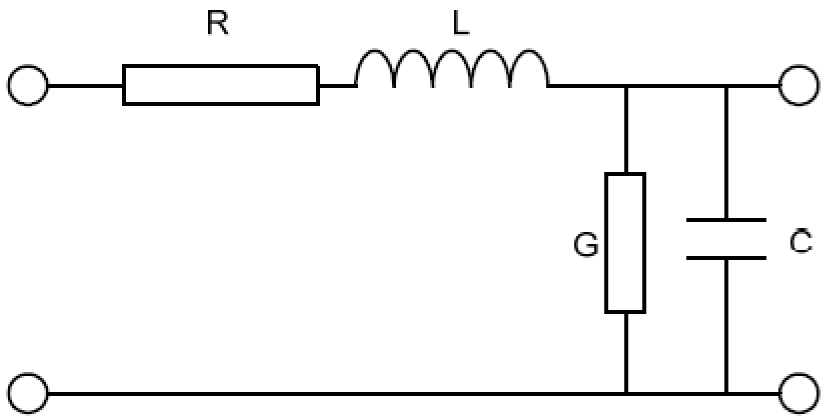

Figure 3.4 Lumped element transmission line model (figure abstracted from Minao and Maffucci, 2001).

3.4 Parameters of Transmission Line

There are four basic parameters of the transmission lines and they are capacitance, conductance, inductance and resistance.

3.4.1 Capacitance

Capacitance occurs between two conductors when there is a potential difference across them. When the potential difference is set up, an electric field is generated between the two conductors. Capacitance is the ratio between the charge stored and the potential difference.

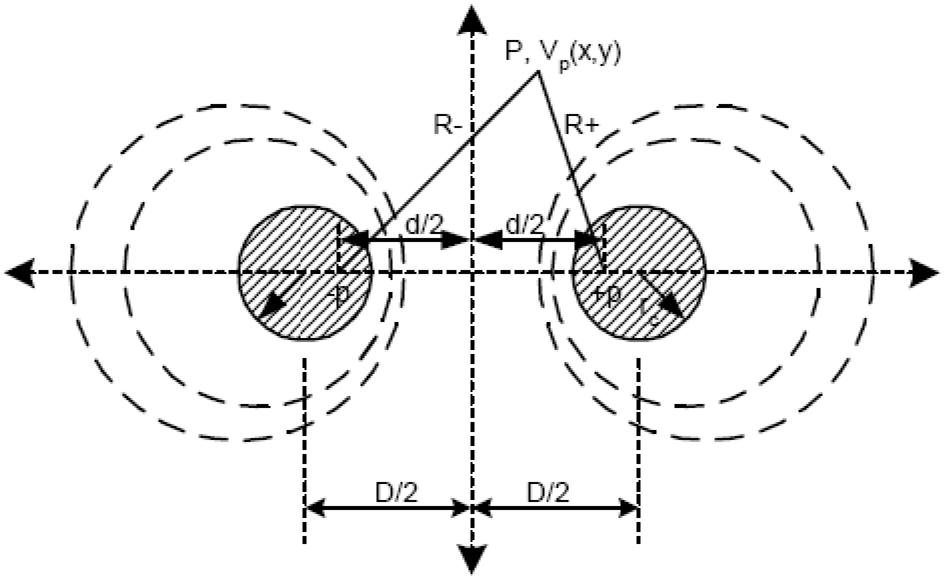

Figure 3.5 Cross sectional view of a two-wire transmission line (figure abstracted from Popovic, 1971).

The potential difference between two points R_a, R_b and a line charge is given by:

$$V = - \rho / (2\pi\varepsilon_0) \text{ In } (R_a / R_b) \quad \text{V} \qquad 3.1$$

where ρ is the charge distribution C/m.

Looking at figure 3.5 and using equation 3.1, the potential at P can be obtained. From the result, it can be determined that in order to produce a particular equipotential surface with a value of V, the ratio between R+ and R- must be a constant, K.

If K is rewritten in the form of an equation for a circle, this would present the equipotential surface with its centre at $x = x_0$ and radius r. if $0 < k < 1$, then the equipotential surface is located on the left half plane and while $1 < k < \infty$, the surface will be located on the right half plane.

The equipotential surfaces can be mapped onto the two conductors in figure 3.5 by replacing at $x_0 = \pm D/2$ and $r = r_c$. The potential difference between the two conductors is the difference between potential of two equipotential surfaces.

Finally by dividing the per unit length charge by the potential difference gives the capacitance between the two conductors.

$$C = \frac{\pi \varepsilon_0 \varepsilon_r}{\ln\left(D/2r_c + \sqrt{(D/2r_c)^2 - 1}\right)} \quad \text{F/m} \qquad 3.2$$

3.4.2 Inductance

There are two different inductances within a transmission line: external and internal. External inductance is the self inductance of the cable. Self inductance can be defined as the generation of an induced voltage on a current carrying cable where the current is charging. The changing current creates a magnetic field between the two conductors which then induces voltage back into the cable.

The relationship given by the equation below is valid for all TEM transmission lines and can be used to calculate the external inductance of a transmission line.

$$LC = \mu\varepsilon \qquad 3.3$$

The inductance per unit length is:

$$L_{ex} = (\mu_0\mu_r / \Pi) \ \ln\{D/2r_c + \sqrt{((D/2r_c)^2 - 1)}\} \text{ H/m} \qquad 3.4$$

Internal inductance comes from the magnetic fields inside the conductors. At high frequencies, where the skin effect phenomenon is dominant, the magnetic flux at the core of the conductors decreases and thus the internal inductance also decreases. The internal inductance is given by:

$\boldsymbol{L_{in}} = \mathbf{R / \omega}$ H/m 3.5

The total inductance of the cable is given by:

$\boldsymbol{L = L_{ex} + L_{in}}$ H / m 3.6

3.4.3 Conductance

Conductance can be defined as the ability of a material to allow electrons to flow. In the case of an insulator, it describes its leakage current. The leakage current is the current flow due to the imperfect insulator, and it travels from one conductor to the other through the insulator. Leakage current is a form of loss for the cable.

By using the TEM relationship, conductance can be acquired.

$\mathbf{G/C = \sigma/\varepsilon}$ 3.7

Conductance per unit length is:

$$G = \frac{\pi\sigma}{\ln\left(D/2r_c + \sqrt{(D/2r_c)^2 - 1}\right)} \quad \text{S/m} \qquad 3.8$$

Furthermore, the conductance per unit length is influenced greatly by the dissipation factor, tanδ of the dielectric material and can also be expressed as:

$G = 2\pi f c.\tan\delta$ 3.9

3.4.4 Resistance

The electrical resistance is the ratio of potential difference to the current flow within a material. At DC, resistance is a function of the geometry of the structure and resistivity of the material. However when the current is replaced with an AC current, resistance becomes more difficult to calculate. The AC resistance now involves the electric and magnetic fields surrounding the material.

When operating in high frequencies, skin effect becomes dominant. Currents concentrate near the conductor's surface and results in internal impedance. This effect causes an increase in resistance and it worsens with an increase in frequency.

For resistance per unit length, considering the fact that this project is dealing in the MHz range, skin effect has to be taken into account and can be expressed as:

$$R = \sqrt{[(\pi\mu_0 f) / (\kappa r^2)]} \qquad (3.10)$$

Where κ is the conductivity of the conductor.

3.5 Transfer Function

The transfer function of a system can be expressed as:

$$\text{Transfer function} = \text{Output} / \text{Input} = Vo/Vi \qquad (3.11)$$

$$\text{Transfer Function, } H(f) = e^{-\gamma d} \qquad (3.12)$$

Where d is the line's length and γ is the propagation constant.

Chapter 4 Measurement Methodology and Discussions

4.1 Frequency Response of the Cable

The Agilent E8358A Network Analyser was used to measure the actual response of a two core TPS cable. The figure below shows a typical E8358A Network Analyser.

Figure 4.1 Agilent E8358A Network analyzer (figure abstracted from Agilent user guide, 2002).

The specifications of the equipment are listed in table 4.1 below:

Agilent E8358A Specifications	
Frequency Counter	300 kHz – 9 GHz with ±0.5 ppm accuracy.
Amplitude Range	20 dBm to -30 dBm
Dynamic Range	128 dB
Sweep speed	35μs/point
Resolution Bandwidth	300 Hz
Connectors	Type N socket

Table 4.2 Agilent E8358A network analyzer specifications.

The measurement uncertainty of the network analyzer is as a result of a combination of the residual systematic (repeatable) errors and the random (non-repeatable) errors (Agilent, 2004).

The systematic errors include: directivity, source match, load match, isolation (cross-talk) and reflection and transmission frequency tracking. The random errors include: drift, connector repeatability and test cable stability.

The accuracy of the measurements of the network analyzer greatly relies on external factors such as interconnecting devices and test components. These are vital factors because they can introduce noise into the results which could alter the actual response of the cable being tested. The Agilent E8358A network analyzer has a few incorporated error correction calculations to compensate for these errors.

To remove these errors, the system is normalized before testing. Only test set-up equipment such as interconnecting cables and connectors are connected to the network analyzer. The system is then regulated in the frequency range selected. The cable to be tested can now be introduced to the system.

Any measurement result is the vector sum of the actual test device response plus all error terms. The precise effect of each error term depends on its magnitude and phase relationship to the actual test device response. When the phase of an error response is not known, phase is assumed to be worst case (-180^0 to $+180^0$). Random errors such as noise and connector repeatability are generally combined in a root-sum-of –the squares (RSS) manner.

4.2 MATLAB Codes

To verify the transmission line model and its distributed parameters, MATLAB codes were generated using the RF toolbox kit and also the M-file. The RF Toolbox enables you to create and combine RF circuits for simulation in the frequency domain with support for both power and noise. It enables a practical analysis and visualization of RF network parameters.

4.3 Testing the Cable Properties

A 1Mhz square wave was generated by a signal generator and transmitted down a 4m cable. Probes from an Oscilloscope was attatched to the input and output end of the cable. The square wave has a peak to peak voltage of 10V to compensate for the unmatched load. The unmatched load created reflected waves which combines with the original signal, producing a much lower voltage at the input. Unfortunately, at any frequencies higher than 1MHz, the signal becomes too distorted to detect any distinct rising or falling edges.

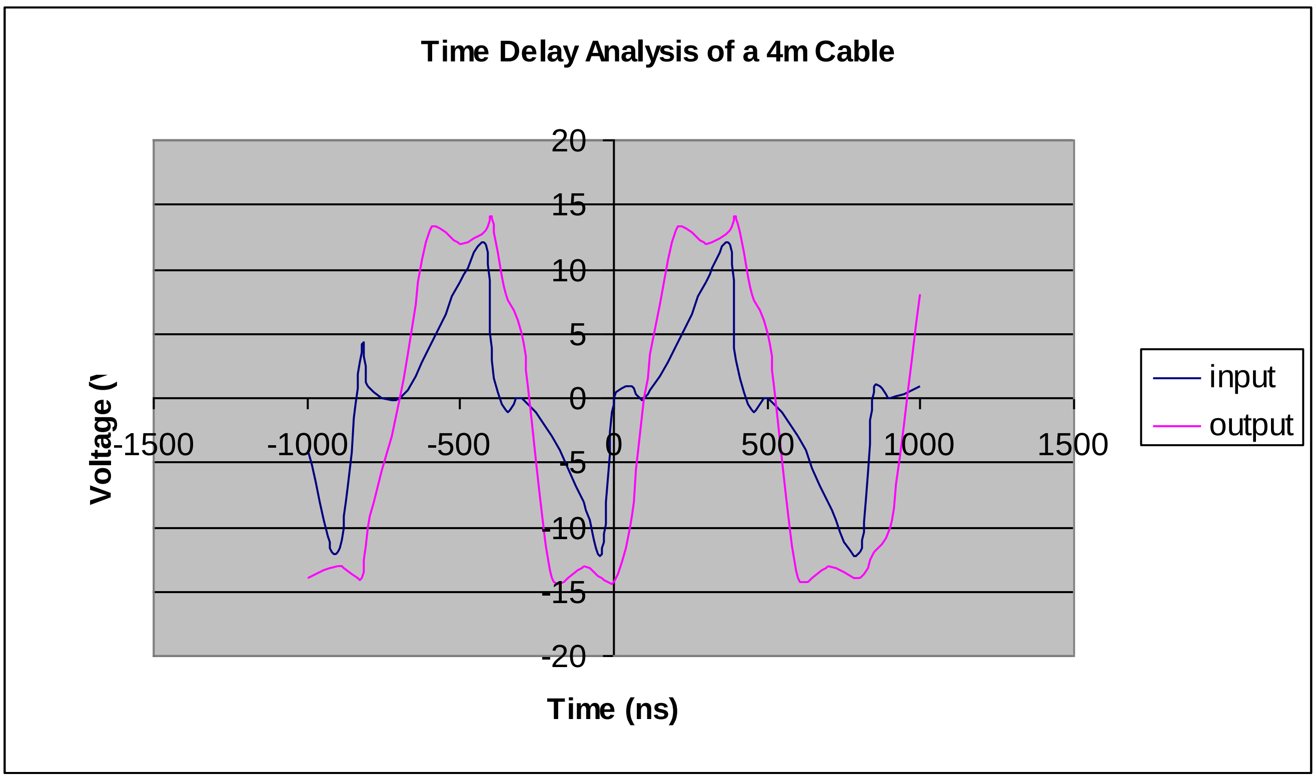

Figure 4.2 Input and output response of a 1MHz square wave signal.

The results of the test are shown in Figure 4.2. It was found that the distance in time between adjacent poles is approximately 36ns. This value signifies that it takes the signal approximately 36ns to travel down the cable.

This value can be used to obtain the velocity of propagation of the signal using the mathematical representation below:

$$\upsilon = 2d / \Delta t \qquad (4.1)$$

Thus, υ = (2 x 4) m / (36 x 10^{-9}) s ≈ 2.22 x 10^{8}m/s.

Therefore, the signal travels with a velocity of 2.22 x 10^{8}m/s. This value seems to be realistic when compared to the speed of light which is definitely supposed to be higher.

Also, the permittivity of PVC can be obtained by re-expressing the phase velocity in equation 4.2 as:

$$\mu_p = 1/\sqrt{(\mu_0\mu_r\varepsilon_0\varepsilon_r)} = l/t \text{ m/s} \qquad (4.2)$$

where $\mu_{0,}$ μ_r *and* ε_0 *are* permeability of free space, relative permeability and permittivity of free space and have values of 4π x 10^{-7} H/m, 1 and 8.854 x 10^{-12} F/m respectively. ε_r represents the permittivity of PVC. Using the formula in equation 4.3, ε_r was calculated for the PVC:

$$\varepsilon_r = t^2 / (l^2\ \mu_0\mu_r\varepsilon_0) \qquad (4.3)$$

Using (4.3) above and the previously calculated value of t, the relative permittivity of PVC is estimated to be 7.28. The range of values of relative permittivity for PVC is 3.4 – 8.0 (Kersting, 2002). Thus, the calculated value (7.28) seems to be a reasonable value considering the fact that it is in the require range.

The value of permittivity of the PVC is very important because it is required for the calculation of capacitance.

4.4 Validation of Transmission Line Model

The transmission line model was designed based on examining the validity of two models when compared to an analytical (actual) model of a transmission line. These models are Lossless Model and Complex exponential model. These models are actually gotten from the lumped element model.

In the analytical model, the complex propagation constant can be determined as:

$$\gamma = \sqrt{[(R + j\omega L)(G + j\omega C)]} \qquad (4.4)$$

$$= \alpha + j\beta$$

Where α is the attenuation constant, β is the phase constant and $\omega = 2\pi f$, where f is the frequency. These two values (α and β) are of great importance when modeling a transmission line, since they describe the behaviour of the electromagnetic wave inside the conductor. The attenuation constant represents the real loss through the conductor and insulation loss. Phase constant represents the phase behaviour due to the complex reactance from the cable.

This complex propagation constant, γ, is valid for all types of TEM transmission lines.

Lossless Model

In the lossless model, the assumptions made is that the cable is a perfect conductor and perfect insulator, i.e $R = G = 0$.

Thus, the propagation constant for a lossless case is:

$$\gamma = j\omega\sqrt{(LC)} = j\beta \qquad (4.5)$$

From (2), we can see that the propagation constant has no attenuation. However a phase change is still present. It is obvious that this model can not be used for this project, as the assumptions made are incorrect for this project.

Exponential Model

In the exponential model, the aim was to model the behaviour of the transmission line to obtain a high degree of accuracy, while still showing analytical calculations to be performed. The model needs to be able to model any attenuation and phase change that might occur at high frequency, thus no assumptions whatsoever are made on this model.

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

$= \sqrt{[RG + j\omega RC + j\omega LG - w^2 LC]}$

Bringing like terms together,

$= \sqrt{[RG - \omega^2 LC + j\omega(LG + RC)]}$

$= \sqrt{(x + jy)}$

$= \sqrt{r}\, e^{j\theta/2}$ (4.6)

Where

$x = RG - \omega^2 LC$ (4.7)

$y = \omega(LG + RC)$ (4.8)

and $r = \sqrt{(x^2 + y^2)}$ (4.9)

$$\theta = \tan^{-1}(y/a) \qquad (4.10)$$

Using (4.10) and exponential properties, the complex propagation constant in (4.4) can be expressed as:

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

$$= \sqrt{r}\cos(\theta/2) + j\sqrt{r}\sin(\theta/2) \qquad (4.11)$$

Where

$$\alpha = \sqrt{r}\cos(\theta/2) \quad \text{Np/m} \qquad (4.12)$$

and $\beta = \sqrt{r}\sin(\theta/2)$ rad/m (4.13)

Unequivocally, (4.12) and (4.13) shows the attenuation constant and phase constant are now defined individually, comprised of the four transmission line parameters (R, C, L and G). This model has more benefits than the lossless model, thus it would serve the objectives of this project. Firstly, it is similar to the original transmission line model, because it makes no assumptions about losses. The other benefit is that there is a formula for both attenuation and phase constant.

To test the two models (exponential and lossless), a MATLAB code was written to test them over a certain frequency range of interest and compare them to the actual model. MATLAB was chosen for this project because it can handle complex arithmetic and can easily give the graphs of any result obtained. Also, it makes reprogramming of codes simple to execute.

Since the parameters have not been actually calculated, the following values were taken from text books.

$R = 1\Omega/m$, $G = 3S/m$, $C = 10nF/m$ and $L = 0.5\mu H/m$.

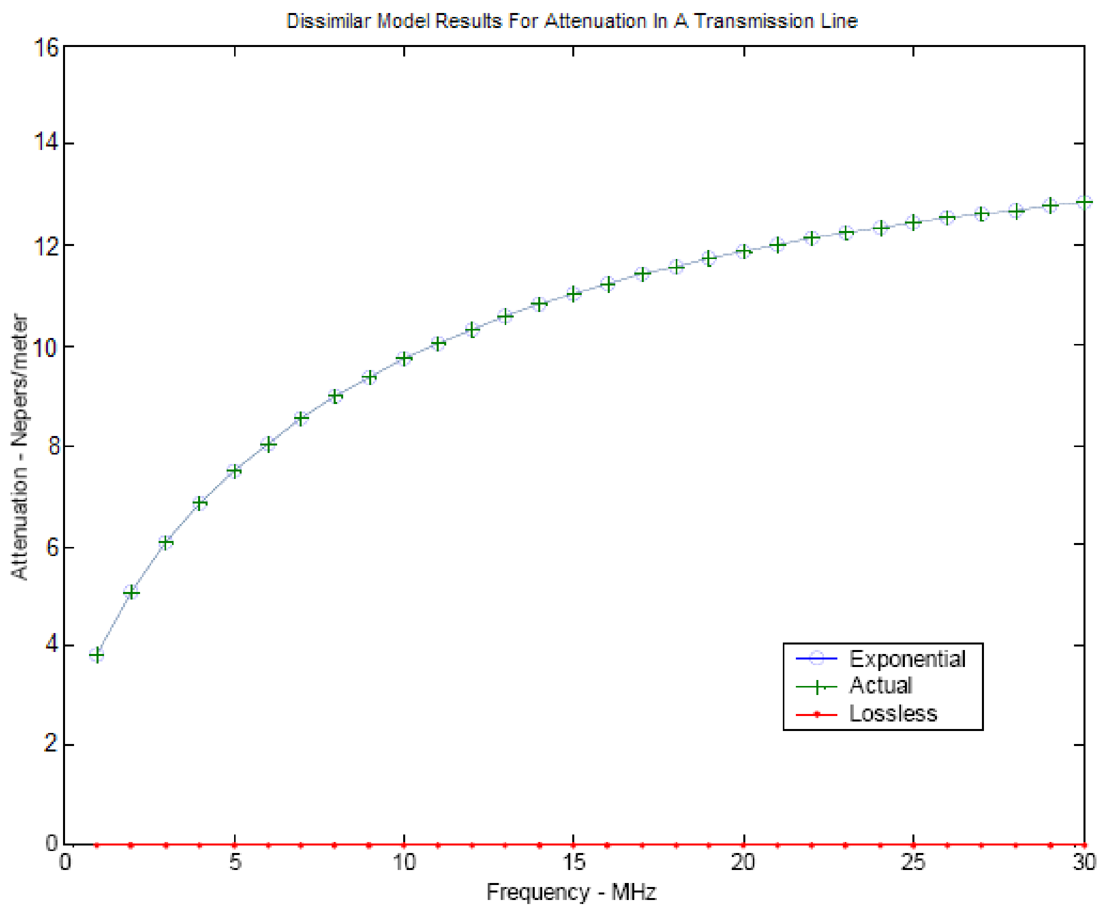

Figure 4.3 Attenuation results of different models from 1MHz to 30MHz.

Figure 4.3 shows how the exponential and lossless models show the effect of frequency on attenuation (compared to the actual model). As expected, the lossless model has no attenuation because of the assumptions made but the exponential model is an exact match to the general case which is represented by the actual model.

4.5 Comparing Results

The measurements were carried out on a 10m two core cable for the frequency band of 0-30MHz and signal coupling by a network analyzer Agilent E8385A. The service power was set to 10dBm and the sweep time was set to a second. The results gotten from the measurements were compared to those from the MATLAB model to check the validity of the power line model. The results are analyzed below.

4.5.1 Attenuation Response

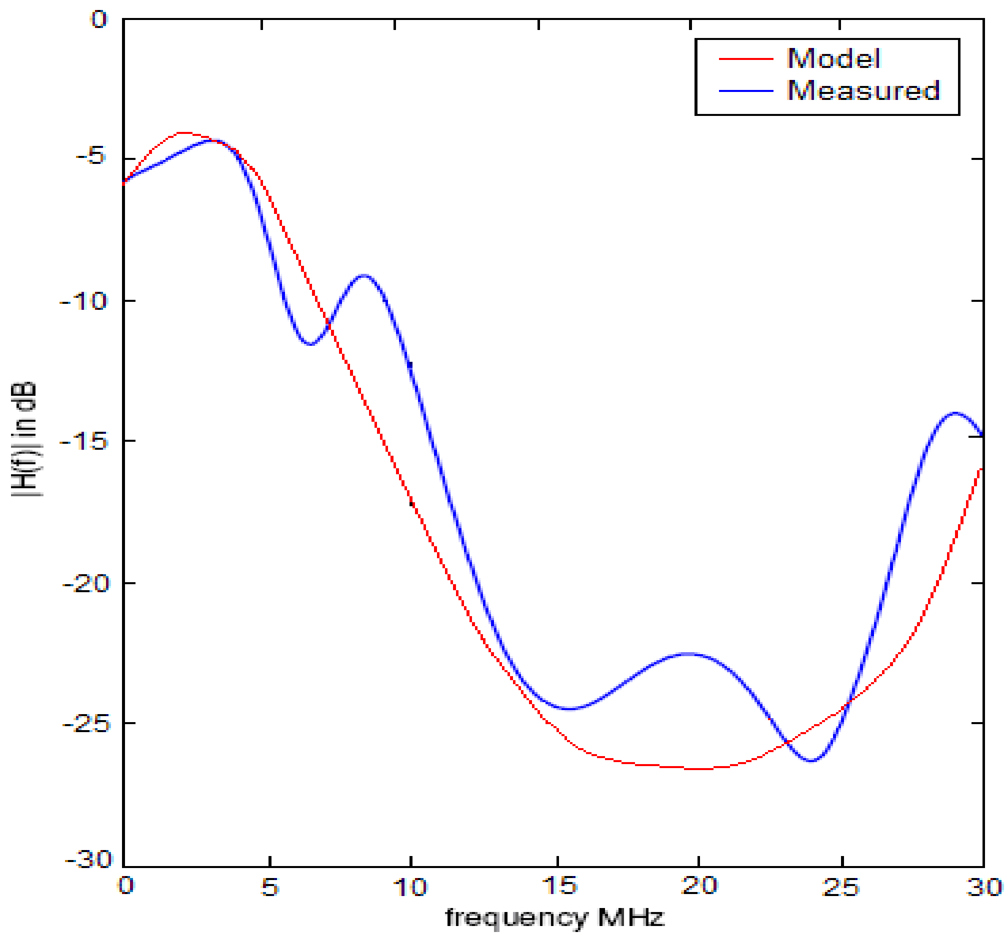

Figure 4.4 Attenuation of a 10m two core cable from 0 to 30MHz.

The figure 4.4 above compares the predicted results of the model and the measured results of the cable. As we can see, the results are not entirely similar but the model does actually predict the trend of the attenuation.

From the graph, the maximum difference between the measured results and the model occurs at about 20MHz, where there is a difference of about 4dB respectively which could be caused by the network analyzer.

The predicted result from the model is a smooth curve through the frequency range with one maximum and one minimum; On the other hand, there are maximums and minimums in the measured results. There are several reasons which could cause this occurrence.

Firstly, the connections that were used on the cable could also reflections within the system. Also, the measured cable had a lot of twists which were inevitable during the measurement. In the case of the model, the distributed parameters are modeled on a very small section of the cable. We would also consider the fact that the model parameters were not obtained. These twisting on the cable could also vary the characteristic impedance of the cable; since the characteristic impedance of the cable is a function of frequency.

Furthermore, the environment where the experiment was carried out played a very important role in the results. The experiment was carried out in the Engineering Laboratory of the Robert Blackburn Building. The Laboratory contains several equipment and metal objects such as tables and chairs that were scattered in the room. Although the equipment were not in use at the time the measurements were carried out, they would have introduced some certain level of noise or interference into the system which could affect the result. Also, the metal objects could have affected the high frequency signal.

These problems could have been avoided, if the experiment were to be repeated. However, these problems are a good representation of a real-life system.

It is very unlikely to find noise or interference in homes as experienced in the laboratory. Thus, measurements carried out in a home might reveal reduced level of attenuations. Although these results are not ideally a clear picture of ideal experimental conditions, they provide a reasonable picture of what attenuation may look like in real-life situation.

By using the attenuation result, the signal strength along any point on the link can be predicted. This can enable the communication designers to determine the maximum cable length allowed for the system and know how to arrange repeaters or bridge taps (if necessary).

In long-haul communications, repeaters are placed at certain intervals to amplify weak signals and relay them along the transmission line. The number of repeaters needed in a communications link depends on the attenuation of the particular transmission medium and the length of the connection.

4.5.2 Phase Response

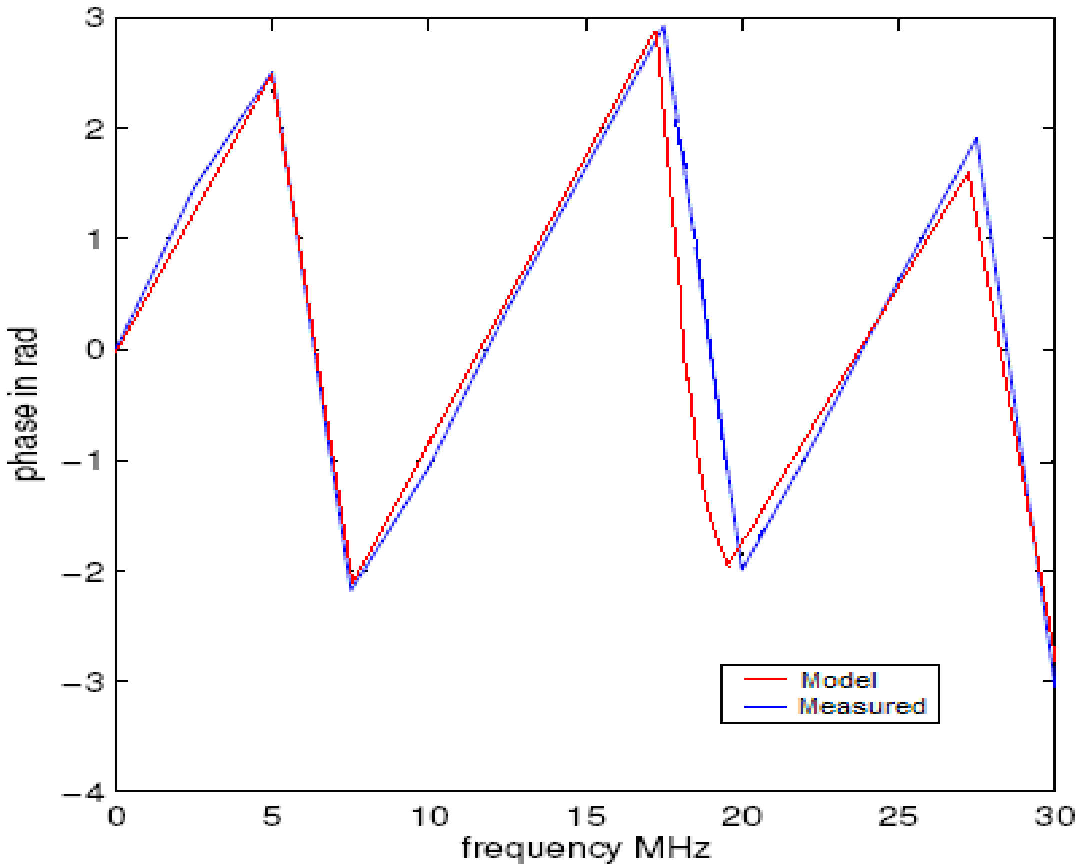

Figure 4.5 Phase spectrum of a 10m two core cable from 0 to 30MHz.

The phase prediction of the model is much more accurate than its prediction on the attenuation. The figure 4.5 above shows how closely matched both sets of the results were. Apart from the very slight differences located between 17MHz to about 28MHz, the results are very similar. On the average, the difference could be about 0.5rad.

We can infer from the results that interference or noise created by the external sources has minimal effect on the phase of the signal transmission unlike what was seen in the attenuation response.

The prediction of the phase change is sacrosanct since the data transfer rate is related to the length of the individual pulses and spacing between the adjacent pulses. With an accurate prediction, maximum data transfer rate of a medium can be achieved.

4.6 Model tests

Further Results for analysis were obtained by modeling different power line communication channels by using different cable lengths and different loading arrangements. All cables used in the model are considered to have RLGC parameters as follows: R = 1.9884Ω/m, G = 0.01686nS/m, C = 0.13394nF/m and L = 362.81nH/m (these values were gotten from a textbook). The transfer function plots for the different arrangements are shown between the frequency bands (0 – 30MHz).

4.6.1 Power line model with different load matching conditions

In the first analysis, the cable lengths and load impedances, Z*l*, were kept constant at 3m and 60Ω respectively while the source impedance, Zs, was varied.

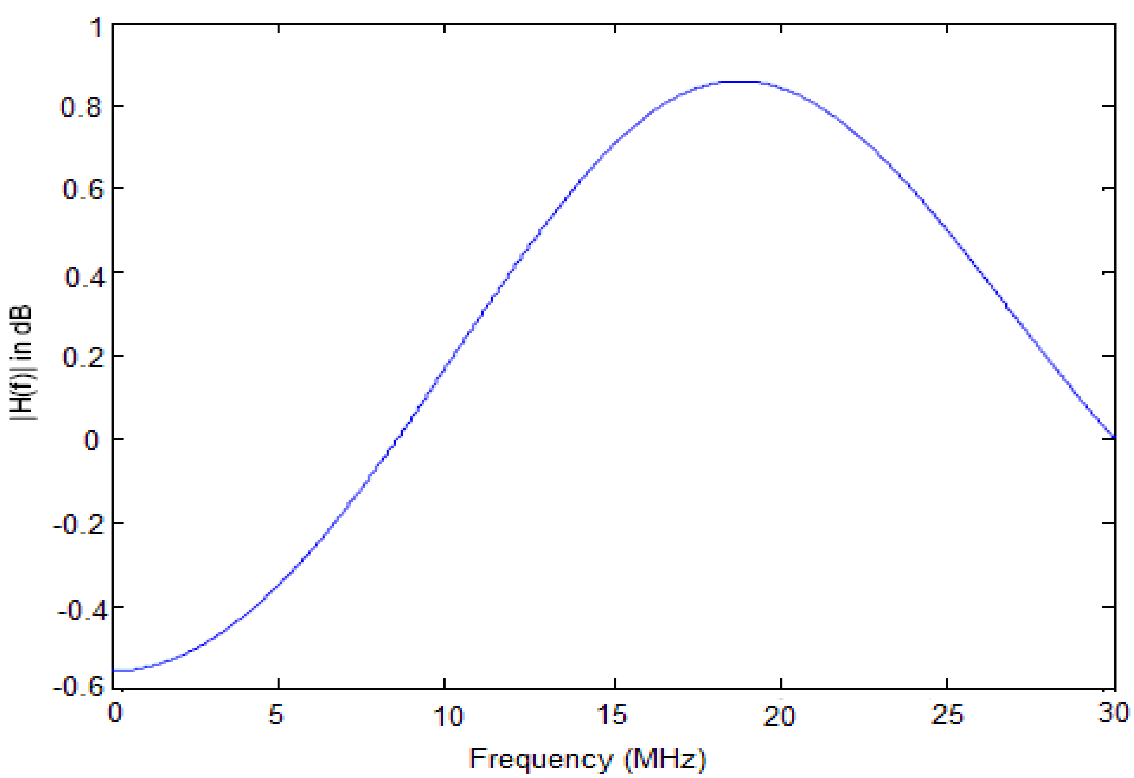

Figure 4.6 Plot of Power Line Model with Zs = 10 and Zl = 60Ω (cable length 3m)

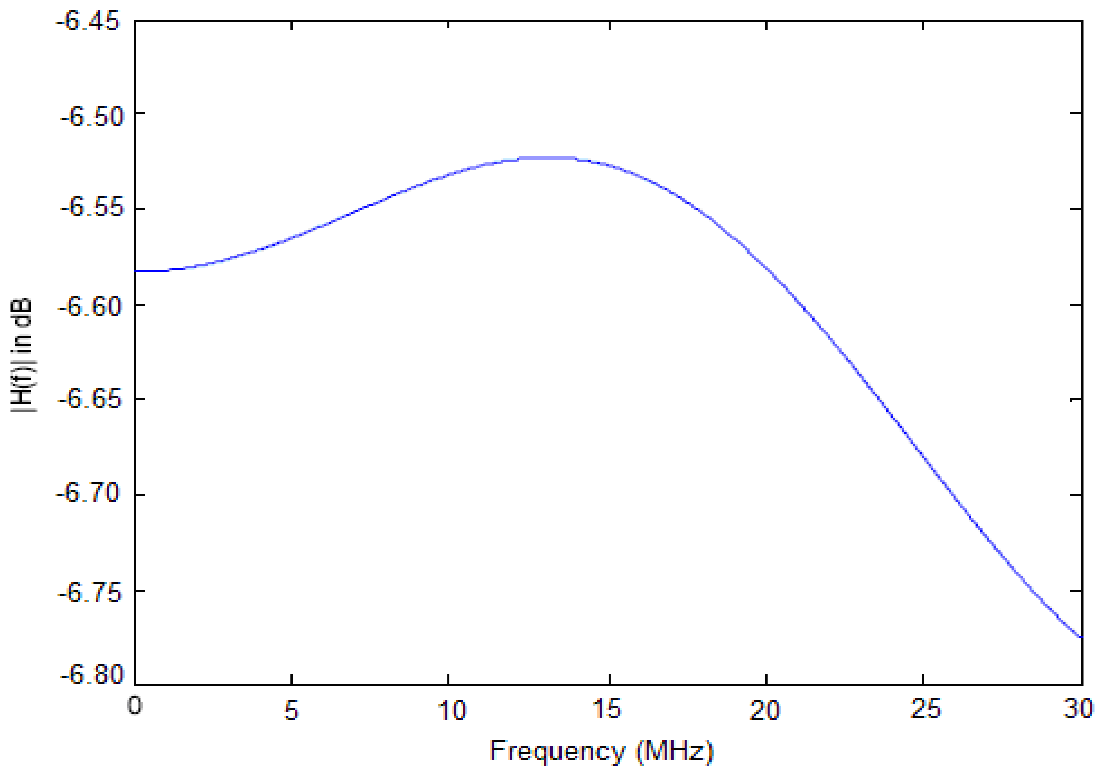

Figure 4.7 Plot of Power Line Model with Zs = 50 and Z*l* = 60Ω (cable length 3m)

Figures 4.6 and 4.7 represent the Transfer function plot of the power line model with varying source impedance and constant load impedance. It can be deduced from the graphs that as the source impedance, Zs, increases, the attenuation increases provided the load impedance, Z*l* is kept constant.

In the second analysis, the source impedance was kept constant at 60**Ω** but the load impedance was varied (with the cable length still desame). The results are shown below:

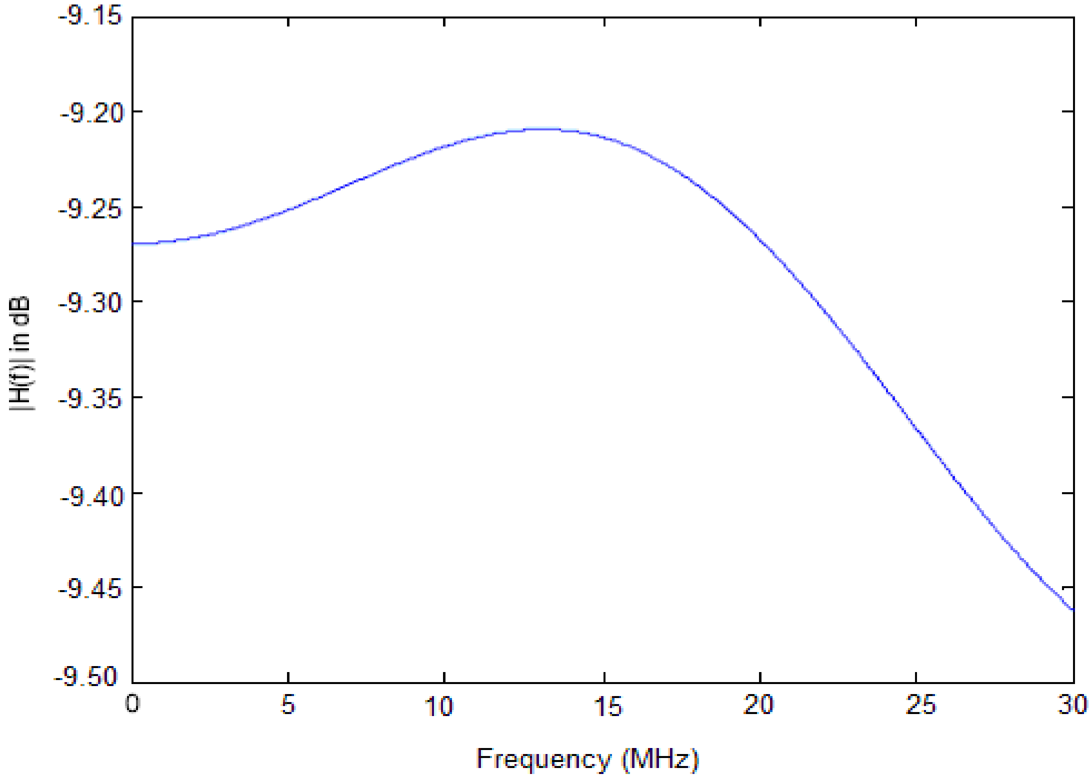

Figure 4.8 Plot of Power Line Model with Zs = 60 and Z*l* = 60Ω (cable length 3m)

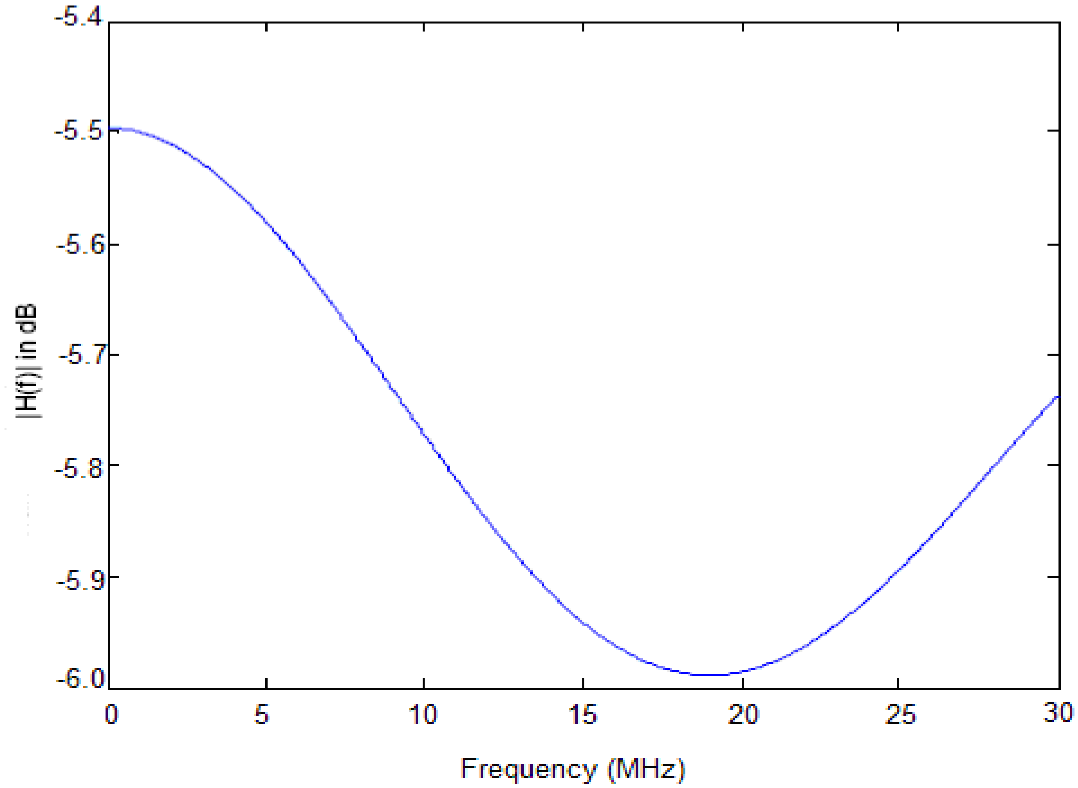

Figure 4.9 Plot of Power Line Model with Zs = 60 and Z*l* = 100Ω (cable length 3m)

Figures 4.8 and 4.9 represent the Transfer function plot of the power line model with varying source impedance and constant load impedance. It can be deduced from the graphs that as the load impedance, Z*l*, increases, the attenuation gradually decreases provided the source impedance, Zs is kept constant.

4.6.2 Power line model with different cable lengths

Transfer function for certain power line configurations was tested. The configuration investigated the effects of varying cable lengths on a transmission line model. The following results were obtained from MATLAB.

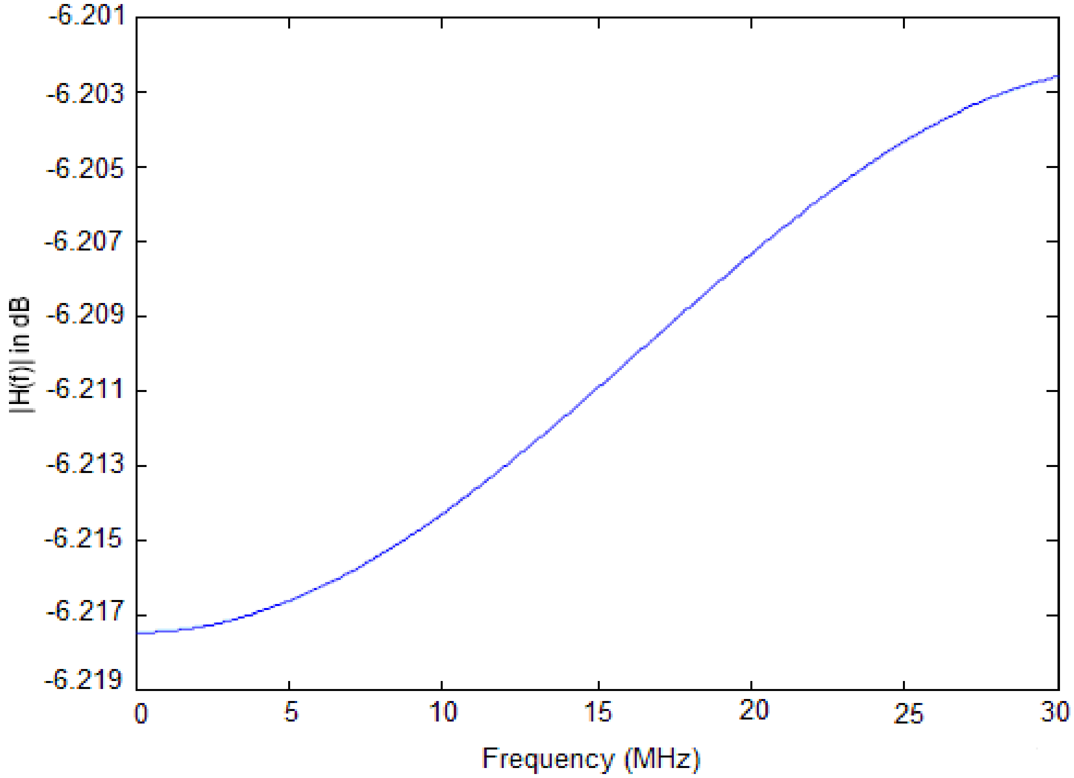

Figure 4.10 Plot of Power Line Model with Zs = 50 and Z*l* = 70Ω (cable length 1.5m)

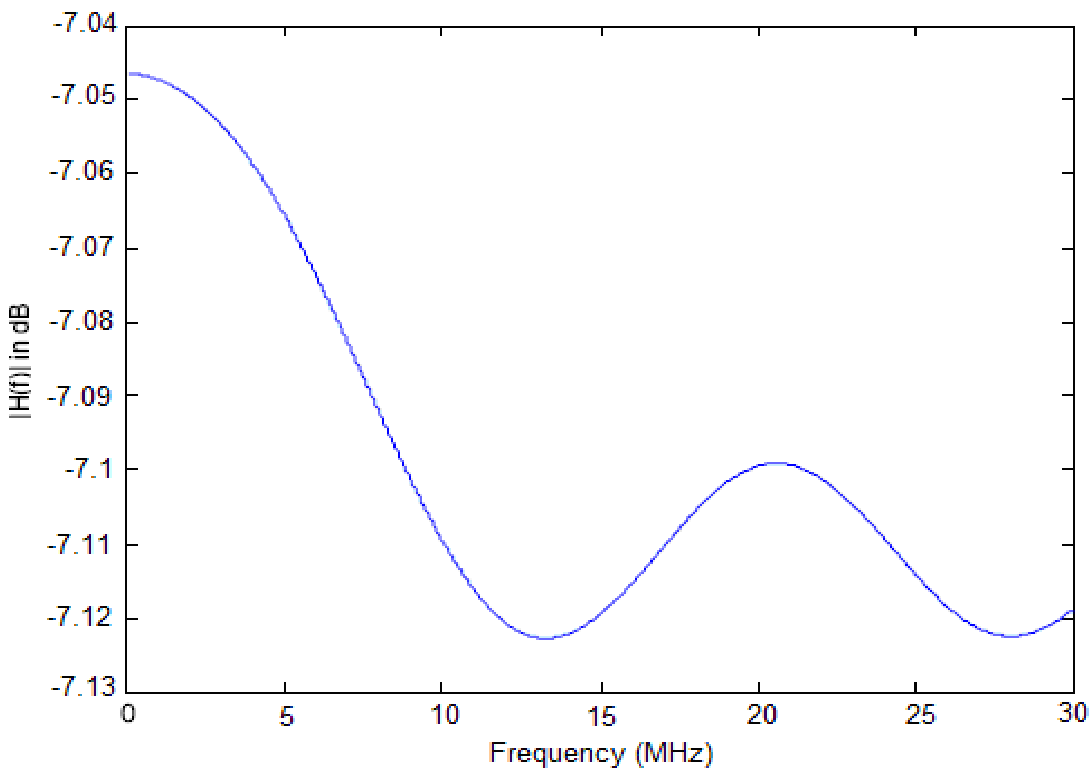

Figure 4.11 Plot of power line model with Zs = 50 and Zl = 70 (Cable length 6m)

From figures 4.10 and 4.11, we can see that as the cable length increases, the attenuation increases gradually. This can be justified with the fact that with longer cable lengths, the signal will be exposed to interference; hence, the signal strength will gradually decrease over distance.

Transfer function plots were used because a transmission channel is characterized by the transfer function between the transmitter and receiver and also the interference that the receiver sees. The transfer functions are temporarily constant and change abruptly with load changes and also cable length changes.

The plots show the effects of cable (channel) length and load impedance on the transfer function plot of the power line communication channel. From these plots, the effects of these quantities can be visibly seen. The analysis reveals that the attenuation of power line increases as the cable length increases. The type of load impedance connected to the transmission line is also seen to have considerable effects on attenuation especially in determining the nature (or shape) of the plot.

The validity of these results cannot be determined since measurements of these arrangements were not carried out but we can see that they show the trend that occurs in real-life systems. These findings enable designers to establish efficient power line communications systems.

5 Conclusion

The two major objectives of the project which were to model a transmission line using MATLAB software and to determine if the model can predict power line behavior such as phase and attenuation were successfully achieved.

Furthermore, the model was used to check the effects of using different loading conditions and cable lengths. The results showed similar trends to real-life systems. They showed that increasing the cable length of the communication channel results in increased attenuation. The validity of these results was not analyzed since measurements were not carried out on the different arrangements.

The experimental analyses were conducted in the Engineering Laboratory of the Robert Blackburn building. Although this was not entirely a suitable location for the experiment, the results obtained were analytical of the nature of the environment that a power line network may face.

The MATLAB program allows for easy upgradeability to model other cables. Thus, any two wire transmission line can be modeled by inserting the new physical dimensions and their electrical properties. This was the main reason MATLAB was chosen for the project.

The Power line Communication field still constitutes an open and attractive research area. Many studies are still essential to better comprehend and improve the performance of power line for high-bit rate transmission.

Noise and multipath propagation are major issues that the power line communication system is facing. They were not appropriately taken into account in this project. More investigation is required in these areas to ensure that a more efficient model can be realized.

5.1 Future Consideration

Further analyses of the results are required to improve the accuracy of the model. Also, noise effects were not considered when deriving the signal propagation. Noise present in the link can cause severe bandwidth limitations upon the channel. These include external noises on the channel and the effect that the 50Hz mains supply has on the attenuating signal.

Impedance is a major contributing factor for modeling the power line channel. More investigation needs to be carried out to find out how impedance mismatches is related to the attenuation in the network.

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Appendix

MATLAB Source Code

```
function [res, rescount, indi, inde, cap, con, gammareal, gammalless, gammace,
scale, count, thetareal, thetace, thetalless, atten_real, atten_ce, atten_lless] = twowire(d, a, uc, oc, ui, oi, ei,
fl, fh, step, inde0, cap0, con0, res0,
indi0, length)
%Constants
j = sqrt(-1);
u0 = 4*pi*1e-7;
e0 = 8.854e-12;
%Counters
counter_real = 0;
counter_lless = 0;
counter_ce = 0;
%Converting frequency input to MHz
fl = fl*1e6;
fh = fh*1e6;
step = step*1e6;
%Beginning of loop to scan through frequency ranges
position = 1;
count = 0;
for index = fl:step:fh;
%Counter for each variable
count = count + 1;
f = index; %Frequency, Hertz
freq = index;
w = 2*pi*f; %Radians/
%If cable properties is 0, or capacitance is set to 0, set capacitance
%to 0 for calculation else use formula
if(d == 0 | a ==0 | cap0 == 0)
cap(count) = 0;
else
cap(count) = (pi*e0*ei)/acosh(d/(2*a)); %complete model
%cap(count) = (pi*a*ei*e0)/(d-(pi*a/2)); %simplified model
end
C = cap(count);
%If cable properties is 0, or inductance is set to 0, set inductance
%to 0 for calculation else use formula
if(d == 0 | a ==0 | inde0 == 0)
inde(count) = 0;
else
if(cap(count) == 0)
inde(count) = 0;
else
%inde(count) = u0*uc*e0*ei/cap(count); %TEM relationship
inde(count) = uc*u0*acosh(d/(2*a))/(pi);
end
end
%If cable properties is 0, or conductance is set to 0, set conductance
%to 0 for calculation else use formula
if(d == 0 | a ==0 | con0 == 0)
con(count) = 0;
```

```
else
%cond = (pi*oi)/acosh(d/(2*a));
%cond = oi*cap/(ei*e0); %TEM relationship
cond = C*23.162*(freq^0.7944); %loss tangent
con(count) = cond;
end
G = con(count);
%If cable properties is 0, or resistance is set to 0, set resistance
%to 0 for calculation else use formula
if(d == 0 | a == 0 | res0 == 0)
res(count) = 0;
R = 0;
rescount(count) = 0;
indi(count) = 0;
else
sd = 1/sqrt(pi*freq*uc*u0*oc); %Skin depth
Rs = 1/(oc*sd); %Resistance of the plane conductor for unit length and
unit width

%Total inductance
L = inde(count) + indi(count);
%Attenuation and Phase
alpha = G*R-(w^2)*L*C;
beta = w*(L*G+C*R);
54
r = sqrt(alpha^2+beta^2);
if alpha>0
if(alpha ~= 0)
theta = atan(beta/alpha);
else
theta = 0;
end
else
if(alpha ~= 0)
theta = atan(beta/alpha)+pi;
else
theta = 0;
end
end
%Propagation Constant - Complex Model
gammace(position) = sqrt(r)*exp(j*theta/2);
%Propagation Constant - Lossless Model
gammalless(position) = j*w*sqrt(L*C);
if(L ~= 0)
RL = R/L;
else
RL = 0;
end
if(C ~= 0)
GC = G/C;
else
GC = 0;
end
%Propagation Constant - Complete Model
gammareal(position) = sqrt((R+j*w*L)*(G+j*w*C));
GAMMA = [gammareal;gammalless;gammallow;gammace];
```

```
%Transfer function
c0 = 3e8;
if((G+j*w*C) == 0)
z0 = 0;
else
z0 = sqrt((R+j*w*L)/(G+j*w*C));
end
impedance(count) = z0;
%Matched or fixed load impedance
zl = z0*1.0;
%zl = 100-10*j;
%Reflection Coefficient
if((zl+z0) == 0)
pl = 0;
else
pl = (zl-z0)/(zl+z0);
end
if(z0 == 0)
alpha = 0;
else
%alpha = R/(2*z0)+(G*z0/2);
end
l = length;
%Attenuation and Phase response - Complete
alpha = real(gammareal(position));
beta = imag(gammareal(position));
55
%atten_real(position) = (abs((exp(-alpha*l)*exp(-beta*j*l)*(1+pl))/(1+pl*exp(-
2*alpha)*exp(-2*j*beta*l))));
atten_real(position) = 20*log10(abs((exp(-alpha*l)*exp(-beta*j*l)*(1+pl))/(1+pl*exp(-
2*alpha*l)*exp(-2*j*beta*l))));
theta_real(position) = angle((exp(-alpha*l)*exp(-beta*j*l)*(1+pl))/(1+pl*exp(-
2*alpha*l)*exp(-2*j*beta*l)));
if(theta_real(position) > 0 && position > 1 && theta_real(position-1) < 0)
counter_real = counter_real + 1;
end
if(position == 1)
thetareal(position) = theta_real(position);
else
thetareal(position) = theta_real(position) - (2*pi*counter_real);
end
%Attenuation and Phase response - Complex
alpha = real(gammace(position));
beta = imag(gammace(position));
%atten_ce(position) = (abs((exp(-alpha*l)*exp(-beta*j*l)*(1+pl))/(1+pl*exp(-
2*alpha)*exp(-2*j*beta*l))));
atten_ce(position) = 20*log10(abs((exp(-alpha*l)*exp(-beta*j*l)*(1+pl))/(1+pl*exp(-
2*alpha*l)*exp(-2*j*beta*l))));
theta_ce(position) = angle((exp(-alpha*l)*exp(-beta*j*l)*(1+pl))/(1+pl*exp(-
2*alpha*l)*exp(-2*j*beta*l)));
if(theta_ce(position) > 0 && position > 1 && theta_ce(position-1) < 0)
counter_ce = counter_ce + 1;
end
if(position == 1)
thetace(position) = theta_ce(position);
else
```

```
thetace(position) = theta_ce(position) - (2*pi*counter_ce);
end
%Attenuation and Phase response - Lossless
alpha = real(gammalless(position));
beta = imag(gammalless(position));
%atten_lless(position) = (abs((exp(-alpha*l)*exp(-beta*j*l)*(1+pl))/(1+pl*exp(-
2*alpha)*exp(-2*j*beta*l))));
atten_lless(position) = 20*log10(abs((exp(-alpha*l)*exp(-beta*j*l)*(1+pl))/(1+pl*exp(-
2*alpha*l)*exp(-2*j*beta*l))));
theta_lless(position) = angle((exp(-alpha*l)*exp(-beta*j*l)*(1+pl))/(1+pl*exp(-
2*alpha*l)*exp(-2*j*beta*l)));
if(theta_lless(position) > 0 && position > 1 && theta_lless(position-1) < 0)
counter_lless = counter_lless + 1;
end
if(position == 1)
thetalless(position) = theta_lless(position);
else
thetalless(position) = theta_lless(position) - (2*pi*counter_lless);
end
%Linear Phase loss or actual
%thetareal = theta_real;
%thetalless = theta_lless;
%thetace = theta_ce;
%Output of various results for debugging
atten_real'
thetareal'
%atten_ce'
%thetace'
%indi
%inde(1)
%con(1)
%res(1)
%cap(1)
%inde(count)
%con(count)
%res(count)
%cap(count)
%count
%Scale for use with graphs
p = 2;
for j = fl:step:fh,
scale(p) = j;
p = p + 2;
end
```