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Development of Methodologies for Deploying and Implementing Local & Medium Area Broadband PLC Networks in Office and Residential Electric Grids

By

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Declaration

I hereby declare that *"Development of Methodologies for Deploying and Implementing Local & Medium Area Broadband Power Line in Residential and Office Electric Grids"* is my original work and it has not been submitted before for any degree or examination at any other University, all sources I have used, consulted or quoted are duly indicated and acknowledged herein.

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Dedication

To God…
To those who let me Be…
To those who let me Become…
To love, patience, strength and Support…
To living miracles Kudakwashe and my Parents: Isaac Tinarwo & Irene Kavhukatema

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Abstract

The use of electrical networks for telecommunications has a long history. It has been known since the beginning of the twentieth century [Ahola03]. The idea of using electrical networks for broadband communications arose in the 1990s [Hrasnica *et al* 04]. Recent and growing research interest has indicated that PowerLine Communications (PLC) is the threshold for achieving broadband delivery particularly in very dispersed and low teledensity areas. Currently, there are numerous PLC trials and commercial deployments underway inside and outside South Africa. Nevertheless, these PLC deployments are very isolated, done without clear methodology and performance remains bound to the physical layout of the electrical network. Because of that high bandwidth broadband PLC systems are prone to poor performance and this in turn limits the acceptance and deployment of this emerging alternative broadband technology. Though, PLC technical challenges are being addressed, there has been little analysis and research work that is focused on the *"Development of Methodologies for Deploying and Implementing Local & Medium Area Broadband Power Line in Residential and Office Electric Grids"* that would lead to broadband PLC being adopted and be of greater use to non-broadband communities of South Africa. PLC is a term describing several different systems using electrical grid distribution wires for simultaneous distribution of data by superimposing an analog signal [Hrasnica *et al* 04]. The research proposed and presented broadband PLC methodologies for typical medium voltage and local voltage PLC networks. These methodologies were implemented and experimented with in configurations which closely mirrored residential and office settings through laboratory and multibuilding experiments using commercial 2nd Generation Mitsubishi Electric PLC technology. Research results presented not only serve to provide insight into broadband PLC but also how it handled broadband applications (communications), competed and compared with other technologies such as Ethernet LAN. In combination with networking communication theories, the research explored and analyzed the extent of PLC in providing broadband communication to residential and office electric grids at the University Fort Hare, Computer Science Department.

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List of Acronyms

AC	Alternate Current
ADSL	Asymmetric Digital Subscriber Line
AMR	Automatic Meter Reading
ARQ	Automatic Repeat reQuest
ASCII	American Standard Code for Information Interchange
ASCOM	PLC System developed by ASCOM PowerLine Communications AG
BASH	Bourne Again Shell
BPL	Broadband PowerLine
CA	Collision Avoidance
CCU	Capacitative Coupling Unit
CD	Collision Detection
CENELEC	European Committee for Electrotechnical Standardization
CoE	Center Of Excellent
CPE	Customer Premise Equipment
CPU	Central Processing Unit
CRC	Cyclic Redundancy Check
CSMA	Carrier Sense Multiple Access
CTMM	City of Tshwane Metropolitan Municipality(South Africa)
CTS	Carrier Frequency Transmission
dB	Decibel
DHCP	Dynamic Host Configuration Protocol
DHCPD	Dynamic Host Configuration Protocol Daemon
DLC	Distribution Line Communication
DNS	Domain Name System
DS2	PLC System developed by Design of Systems on Silicon Company
DSL	Digital Subscriber Line
EMC	Electromagnetic Compatibility

EnBW	Energie Baden Wurttemberg AG(Utility company in Germany)
ENDESA	Empresa Nacional de Electricidad S.A.(Spain)
ENEL	Ente Nazionale Energia Elettrica(Italy)
ENF	Endesa Net Factory
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FD	Frequency Division
FEC	Forward Error Correction
FTP	File Transfer Protocol
GB	GigaByte
GHz	GigaHertz
GNU	Computer Operating System composed entirely of Free Software
GTS	Goal Technology Solutions (in South Africa)
HE	Head End
HF	High frequency
HomePlug	HomePlug PowerLine Alliance
HV	High Voltage
Hz	Hertz
ICASA	Independent Communications Authority of South Africa
ICT	Information and Communications Technology
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISC	Internet Software Consortium
ISDN	Integrated Services Digital Network
ISP	Internet Service Provider
IT	Information Technology
ITU	International Telecommunication Union
KB	Kilobyte
Kbps	Kilobits per second
LAN	Local Area Network
LV	Low Voltage

MAC	Media Access Control
MAN	Metropolitan Area Network
MB	Megabyte
Mbps	Megabits per second
MHz	MegaHertz
MTR	Mean Time to Repair
MTT	Massive Technology Trial(Zaragoza PLC case study in Spain)
MV	Medium Voltage
MVV	Münchner Verkehrsverbund (Utility Company in Germany)
OPERA	Open PLC European Research Alliance
OSS	Open Source Software
PLC	PowerLine Carrier/Communication
PLN	PowerLine Networking
PLT	PowerLine Telecoms
POP	Point of Presence
PPC	PowerPlus Communications(Utility Company in Germany)
PROFTPD	Professional File Transfer Protocol Daemon
PUA	PLC Utilities Alliance
QoS	Quality of Service
RAM	Random Access Memory
RFC	Request For Comments
RPC	Residential PowerLine Circuit(LV network)
RWE	Rheinisch-Westfälische Elektrizitätswerke(a Germany Power Company)
SMME	Small Medium and Micro Enterprise
STANSA	Standards South Africa
TCP	Transmission Control Protocol
TD	Time Division
USB	Universal Serial Bus
UTL	Uganda Telecommunications Limited
UTP	Unshielded Twisted Pair
VoD	Video on Demand

VoIP	Voice over Internet Protocol
VoPLC	Voice over PLC
Wi-Fi	Wi-Fi Alliance (consortium of companies based on IEEE 802.11 standards)

Chapter One

Introduction

The purpose of this chapter is twofold: 1) to provide underlying reasons for research described in the thesis and 2) present research goals and research approach towards corresponding answers. It serves as an introduction to the research and to the chapters that follow. In the general introduction, the need for broadband PowerLine Communications (PLC) research work is discussed with an overview of some basic concepts and terminologies on which the research is based. A brief discussion is presented to provide an overview of the history, background and current state of broadband PLC. Thereafter, the problem statement is provided, followed by research goals that guide investigation of the research. This is followed by a brief section that present and clarifies the scope of research detailing methodology used for investigating the research problem highlighted. The final section is devoted to the description of the thesis structure and conclusion of the chapter.

1.1 Background of the Study

The use of electrical networks for telecommunications has a long history [Ahola03]. It is not a new thought. It has been known and discussed for decades since the beginning of the twentieth century. The early history of PLC is introduced by [Hrasnica *et al* 04] and according to his book the idea of using electrical wiring for carrier frequency transmission (CTS) of voice over high voltage transmission networks began in the 1920's. It was important for management and monitoring purposes, because at the beginning of electrification there was no full telephone network coverage. Due to the favorable transmission characteristics, [Hrasnica *et al* 04] stated that the maximum distance between transmitter and receiver could even be 900 kilometers with a transmit power of 10 W. High voltage (HV), medium voltage (MV) and low voltage (LV) networks have been used for internal communications by electrical utilities for the implementation of remote measuring and control tasks for quite some time now.

The idea of using these electrical networks for broadband communications arose in the 1990's along with the development of the Internet and digital signal processors [Hrasnica *et al* 04], [Ntuli *et al* 06]. From then on as confirmed by [Ahola03] and [Zuberi03] research on channel characteristics, digital modulations, error detection methods, and error correction methods in PLC increased dramatically. As a result, several integrated circuits providing multi-megabyte data transfer rates per second over electrical networks were introduced and field trials were carried out [Newbury *et al* 03]. In PLC systems, electrical networks are not only used for energy transmission, but also are utilized as a medium for data communication [Little04],[Gent *et al* 03] that allows end-users to use the already existing electrical grid to connect home appliances to each other and to the Internet. This enables networks utilizing PLC to control anything which plugs into the alternating current (AC) outlet. Therefore, internal electrical installations in buildings and homes can use PLC for various communications applications such as lights, television, alarms and intercoms among other things [Hrasnica *et al* 04].

Broadband PLC, (also called Mains Communication, PowerLine Telecoms (PLT), PowerBand or PowerLine Networking (PLN)) is a term describing several different systems using electrical distribution wiring for simultaneous distribution of data. The carrier transmits or communicates voice and data by superimposing an analog signal over the standard 50 or 60 Hz alternating current [Ahola03], [Hrasnica *et al* 04]. In that sense PLC seems to be a cost-effective solution for last mile communications networks because it utilizes the already existing electrical cabling. Generally, PLC systems are divided into two groups: narrowband PLC allowing communications services with relatively low data rates ensuring various automation and control applications as well as a few voice channels [Hrasnica *et al* 04] and broadband PLC allowing data rates beyond 2 Mbps and, accordingly, offering a number of typical telecommunications services in parallel, such as telephony and seamless Internet access [Hrasnica *et al* 04].

Electric utility providers use narrowband PLC for energy-related services. Nowadays, narrowband PLC systems provide data rates up to a few thousand bits per second [Little02], [Sartenaer04]. A comprehensive description of various narrowband PLC systems, including their development can be found in [Dostert01] as cited by [Hrasnica *et al* 04]. However, to sketch the possibilities of narrowband PLC, a very important area for application of narrowband PLC is home automation. Because PLC based automation systems are deployed without installation of additional communications networks cost is significantly decreased [Mohamad06]. Automation systems by narrowband PLC can be applied to different tasks carried out within buildings for example control of various illumination, heating, air-conditioning and security devices [Zuberi03].

Broadband PLC systems provide significantly higher data rates than narrowband PLC systems. Where narrowband PLC networks offer only a small number of voice channels and data transmission with very low bit rates, broadband PLC offer more sophisticated telecommunication services, multiple voice connections, high-speed data transmission, transfer of video signals, and narrowband services as well [Marie *et al* 05],[Lee *et al* 03]. And presently broadband PLC systems such as the 2nd generation Mistubishi Electric chip used in this research provide data rates of 200Mbps both in MV and LV networks [Mitsubishi03]. Hence, broadband PLC is considered capable of telecommunications. Broadband communications services over electrical grids offer a great opportunity for cost-effective telecommunications networks [Little04], [Hrasnica *et al* 04].

Broadband PLC falls into two broad distinct categories, which are classified as MV and LV PLC. The MV PLC is capable of providing broadband data transmission and an extra link where telecommunication networks do not reach without expensive infrastructure extensions. MV PLC technologies are responsible for sending data over to the LV electric networks that connect the consumer homes to the electric utility provider [Vazquez *et al* 05]. The MV PLC enables a last mile local loop solution which provides individual homes with broadband connectivity. It is usually used for connections bridging distances of several hundreds of meters. Typical application areas for such systems are connection of local area networks (LAN) between buildings or within a campus and connection of antennas and base stations of cellular communications to backbone networks [Hrasnica *et al* 04].

LV PLC is used for the last mile telecommunication access networks. It communicates data exclusively within consumer premises and extends connectivity to all electrical outlets within the premises [Vazquez *et al* 05]. The same electrical outlets providing alternating current will now act as network points for broadband PLC devices. Broadband PLC communication provides new and interesting business opportunities. MV PLC solution, combined with LV PLC allows utilities companies and organizations to offer cost-effective, wide-coverage and broadband data services [Newbury *et al* 03], [Naidoo07]. The MV PLC closes the gap between LV networks and telecommunication networks. Because of the importance of telecommunication access, current developments on broadband PLC are mostly directed toward applications in access networks.

In this research, discussion is limited to LV PLC technologies with communication intended for consumer usage (residential and office electric grids) where electrical grids are owned privately or owned and operated by an administrative entity. In addition terms Broadband PowerLine (BPL) or PowerLine Carrier (PLC) or Residential PowerLine Circuit (RPC) or Distribution Line Communication (DLC) systems refers to the LV part of the electrical power distribution network. Basically LV comprises everything attached to the secondary side of the distribution transformer that is MV to LV transformer including LV network within customer premises and all loads attached to it [Castro *et al* 05],[Hrasnica *et al* 04],[Zuberi03].

1.2 Problem Statement

Recently, there has been a lot of interest to utilize electrical infrastructure for broadband communication services. Broadband PLC maybe the suitable technology for broadband home networking and last-mile Internet access for rural areas connected to electric grids [Hrasnica *et al* 04] since there is no much hope for low cost telecommunications infrastructure particularly in very dispersed and low teledensity areas. Growing interest in broadband PLC [Anatory *et al* 07] is such that many trials in residential and office environments are currently being done [Little04], [Arriola05], [Newbury *et al* 05]. But, these broadband PLC deployments are very isolated, done without clear methodology and performance remains bound to the physical layout of the electrical network. Hence, advertised high bandwidth broadband PLC systems are simply prone to poor performance and this in turn limits the acceptance and deployment of this emerging broadband technology.

Given that broadband PLC deployments have been isolated, haphazard and that there is still widespread skepticism [Hrasnica *et al* 04] regarding PLC as a broadband delivery technology even in South Africa [Kuun05], [Kuun06], [Naidoo07]. This research argues that "*Development of Methodologies for Deploying and Implementing Local & Medium Area Broadband Power Line in Residential and Office Electric Grids*" would lead to broadband PLC being adopted. This will present an opportunity for the developing world and will be of greater use to non-broadband communities of South Africa. As a result, the study is undertaken to investigate whether broadband PLC networks have performance comparable to that of the existing broadband technologies. The study will like to strongly argue that if broadband PLC is implemented by following deployment methodologies plus technological advancement it would offer broadband services efficiently and effectively as other existing broadband technologies such as Ethernet LAN.

1.3 Research Goals

Despite the fact that research on broadband PLC has concentrated on home automation, broadband communications and transfer in LV distribution networks, the question on the development of broadband PLC deployment methodologies is still unresolved. There has not been much carried out in terms of research that is focused on broadband PLC deployment methodologies that are cost effective in residential and office electric grids. Therefore, the first objective of the research is:

- *Developing methodologies for deploying broadband PLC in residential and office settings acknowledging reliability and redundancy given the noise level on PLC.*

However, the focus is not only on developing broadband PLC methodologies, but testing these methodologies under realistic network traffic conditions. As a result, we need practical experiments to demonstrate performance and applicability of PLC methodologies in data delivery and in comparison with Ethernet LAN. As a result, the second objective of the research is:

- *To execute exhaustive experiments on broadband PLC in three environments which closely mirror residential and office settings.*

Research on broadband PLC is relatively new and relevant information is still very scattered and not easily available for research purposes. Commercial providers hold most of the available data concerning the locations where broadband PLC is commercially available and actually being tested. For the reason that there is lack of collective literature on broadband PLC, the third objective of the research is:

- *To undertake a comprehensive presentation of broadband PLC case studies literature and a detailed analysis of deployments currently being undertaken in the broadband PLC research area.*

1.4 Contribution of the Thesis

The contribution of this research is to give implementation information to the broadband PLC body of knowledge necessary for developing and deploying broadband PLC in office and residential grids using efficient and effective deployment methodologies. This is achieved through explanation and analysis of broadband PLC network deployments, important characteristics, environments for data transmission through MV or LV grids and the implementation solutions to be considered. The research work presented in the thesis could be helpful in designing suitable broadband PLC networks with better data transfer and performance. As a result, government and organizations will be able to deliver and meet broadband requirements of communities using broadband PLC deployment methodologies discussed and contributed by this research at low cost regardless of differing socio-economic conditions in South Africa. This will indeed increase broadband PLC technology adoption in the broadband market.

1.5 Scope of the Work

In order to achieve the research goals mentioned in section 1.3, a technical study of broadband PLC is essential, accompanied by a wide research of broadband PLC deployment case studies. The literature and case studies are reviewed to provide background knowledge necessary for understanding, developing and investigating deployment methodologies that will offer PLC as a solution for broadband services. Center of Excellence in the Developmental e-Commerce at the University of Fort Hare embarked on broadband PLC research since 2002 [Ntuli *et al* 06] and it is against such a background and platform that the research is constructed. Consequently, there was a great span of research collaboration encompassing complementary projects done within similar research frameworks [Mandioma04], [Ranga05]. Gathering information, data, and external experiences are part of the research. Taking part in conferences [Tinarwo *et al* 06], [Tinarwo *et al* 07] and visiting or contacting companies or people with broadband PLC application experiences was essential in gaining know-how and external knowledge on broadband PLC.

Since the research is focused on PLC methodologies development much emphasis and discussion is given to factors considering, how we developed and experimented with broadband PLC methodologies in supporting the delivery of broadband. The research work comprised developing MV and LV PLC deployment methodologies. The applicability of these PLC methodologies is determined by performing throughput tests in three experiment environments. The LV distribution network and the devices connected to the network determine the experimental network characteristics. So, the structure of the LV distribution network is analyzed. The components of the LV network, which are power cables, electrical distribution boxes, AC sockets, electrical phases, and appliances connected or attached to the LV grid, are surveyed. Implementation of broadband PLC experiments was done in laboratory and multibuilding settings. The equipment based on Mistubishi Electric PLC chip technology purchased from Goal Technology Solutions (South African Company) was implemented over the Computer Science Department LV distribution network. Experiment setups are carefully designed and executed to analyze and evaluate how PLC supports broadband services. The outcome of these experiments shall be the basis for deciding whether broadband PLC has the potential for large-scale deployments.

The research work is based on the theory of topology, computer networks [Tanenbaum03], and undertaking extensive data transfer experiments in the laboratory and multibuilding environments. Because of the complexity of the electromagnetic phenomena in the LV distribution grid the importance of extensive laboratory measurements is considerable. The research focus is on broadband PLC therefore narrowband PLC systems are not discussed. The research work does not focus on modulation techniques, communication protocols or on formation of new communication channel models. The goal of the research as mentioned previously in section 1.3 is to give insight into the characteristics and arrangement of broadband PLC components on an LV distribution network by developing and testing PLC deployment methodologies that are economically feasible for broadband solutions.

1.6 Structure of the Thesis

This section gives an overview of the thesis and how the chapters are organized. The thesis consists of six chapters detailing how the research was undertaken and providing comprehensive deductions to the research topic. The summary of each chapter is given in the introduction section of that particular chapter. Chapter 1 introduces the research by presenting background to the study and does a brief literature review of related work in relevant areas. It provides the underlying reasons for the research, presents the research problem and the approach used to reach the corresponding solutions. The focal point of Chapter 2 is literature review that discusses PLC case studies in light of the role of PLC in broadband delivery. This chapter gives the reader an idea of the on-going trials and commercial broadband PLC projects. The chapter draws on country-specific case studies on broadband PLC promotion and delivery, including countries outside and inside of Africa thus providing background knowledge that would be necessary in developing broadband PLC methodologies in Chapter 3.

The objective of Chapter 3 is comprehensive presentation and discussion of the developed and proposed MV and LV methodologies for deploying broadband PLC residential and office electric grids. The major implementation aspects, advantages and disadvantages of each methodology are described. Moreover, the integration of these methodologies into testable experiments is provided in Chapter 4. Chapter 4 presents the implementations and experiments done in three different deployments that closely mirror residential and office methodologies developed in Chapter 3. It comprises identification of distinct measurement experiments, their design and execution. The experiments also tested the performance of broadband PLC in comparison to Ethernet. In Chapter 4 is where the 2nd generation Mitsubishi PLC System is implemented and the applicability of the PLC methodologies is tested through extensive data transfers tests. The networking and technical description of broadband PLC technology deployed is also presented. Chapter 5 describes the results and presents the evaluations of the research. The goals of the measurements are stated, described and the results are analyzed. It discusses the validity of the developed PLC methodologies inline with experiment configurations done under varying file load scenarios. Chapter 6 concludes the thesis by presenting a research summary, revisiting the objective of the research and discussing possible research contributions. In addition, it presents and discusses potential subjects of interest for future research.

1.7 Conclusion

The current chapter introduced the research study on broadband PLC by presenting background to the study, stating research goals and addressing the methodology followed in accomplishing the research work. The chapter has described and discussed need for broadband PLC research and did a brief literature review of related work in relevant areas with an overview of some basic concepts and terminologies on which the research work is based. The chapter has conferred broadband PLC as an emerging broadband technology with potential equivalent to existing broadband technologies. It discussed the LV and MV PLC systems. It summarized the research undertaken, contribution of the research and concluded with the structure of the thesis. To give the reader an idea of the on-going broadband PLC trials and commercial deployments Chapter 2 reviews and discusses literature on broadband PLC deployment case studies highlighting the role of PLC in broadband services and delivery inside and outside of South Africa.

Chapter Two

Reviewing PowerLine Communication Channel Noise and PLC Implementation Case Studies

Electrical supply networks are not designed for communications and therefore, they do not represent a favorable transmission medium. Accordingly, the transmission characteristics of powerline channels are not favorable for data transfer. So the first part of this chapter introduces noise types and explains the principles of modulation techniques. Also the error handling mechanisms commonly in practice are explored. Since error-handling mechanisms can be applied to the PLC systems to solve the problem of transmission errors. The discussion will focus on the data transmission techniques related to the PLC environment. The second part of this chapter highlights the previous work done by academia and the industry in relation to broadband PLC case studies. It describes broadband PLC trials and commercial deployments and gives a comprehensive reference list of deployments and analysis of broadband PLC deployments undertaken inside and outside of South Africa that looked promising at the time of this writing. The intent is to point out the value each case study offers, and then draw conclusions in the final section of this chapter.

2.1 Noise Description

Before reviewing the PLC case studies within and outside South Africa (section 2.4), it is worthy to highlight noise prevalent in the PLC environment. The power cables and wires were designed only for energy transmission and there are a wide variety of appliances, with different load properties that vary the characteristic impedance of the line connected to the power network. Therefore, the medium for information transmission is subjected to noise [Mohamad06], [Ahola03]. Besides the distortion of the information signal, owing to cable losses and multipath propagation [Anatory *et al* 07], noise superposed on the signal make correct reception of information more difficult. A lot of investigations and measurements were made in order to give a detailed description of the noise characteristics in a PLC environment. [Hrasnica *et al* 04] classifies the noise as a superposition of five noise types, distinguished by their origin, time duration, spectrum occupancy and intensity. These are colored background noise, narrowband noise, periodic asynchronous impulsive noise, periodic synchronous impulsive noise and asynchronous impulsive noise. A brief explanation of these types of noises is presented below.

2.1.1 Colored Background Noise

The power spectral density of colored background noise (type 1), is relatively lower and decreases with frequency. This type of noise is mainly caused by a superposition of numerous noise sources of lower intensity [Sartenaer04]. Contrary to the white noise, which is a random noise has a continuous and uniform spectral density that is substantially independent of the frequency over the specified frequency range [Hrasnica *et al* 04]. The colored background noise shows strong dependency on the considered frequency. The parameters of this noise vary over time in terms of minutes and hours.

2.1.2 Narrowband Noise

Narrowband noise (type 2), which most of the time has a sinusoidal form, with modulated amplitudes. This type occupies several sub-bands, which are relatively small and continuous over the frequency spectrum [Sartenaer04]. This noise is mainly caused by the ingress of broadcast stations over medium- and shortwave broadcast bands. Their amplitude generally varies over the daytime, becoming higher by night when the reflection properties of the atmosphere become stronger.

2.1.3 Periodic Asynchronous Impulsive Noise

Periodic impulsive noise, asynchronous to the main frequency (type 3), with a form of impulses that usually has a repetition rate between 50 and 200 kHz, and which results in the spectrum with discrete lines with frequency spacing according to the repetition rate [Sartenaer04]. This type of noise is mostly caused by switching power supplies. A power supply is a buffer circuit that is placed between an incompatible source and load in order to make them compatible. Because of its high repetition rate, this noise occupies frequencies that are too close to each other, and builds therefore frequency bundles that are usually approximated by narrow bands.

2.1.4 Periodic Synchronous Impulsive Noise

Periodic impulsive noise, synchronous to the main frequency (type 4), is impulses with a repetition rate of 50 or 100 Hz and are synchronous with the main powerline frequency. Such impulses have a short duration, in the order of microseconds, and have a power spectral density that decreases with the frequency [Hrasnica *et al* 04]. This type of noise is generally caused by power supply operating synchronously with the main frequency, such as the power converters connected to the mains supply.

2.1.5 Asynchronous Impulsive Noise

Asynchronous impulsive noise (type 5), is type of noise whose impulses are mainly caused by switching transients in the networks. These impulses have durations of some microseconds up to a few milliseconds with an arbitrary inter-arrival time [Sartenaer04]. Their power spectral density can reach values of more than 50 dB above the level of the background noise, making them the principal cause of error occurrences in the digital communication over PLC networks. Undertaken measurements have generally shown that noise types 1, 2 and 3 remain usually stationary over relatively longer periods, of seconds, minutes and sometimes even of some hours. Therefore, all these three can be summarized in one noise class, which is seen as colored PLC background noise class. According to [Hrasnica *et al* 04] the power spectral density of the generalized background noise can be explained using the following form:

$$N_{\mathrm{GBN}}(f) = N_{\mathrm{CBN}}(f) + N_{\mathrm{NN}}(f) \tag{2.1}$$

$$N_{\mathrm{GBN}}(f) = N_{\mathrm{CBN}}(f) + \sum_{k=1}^{B} N_{\mathrm{NN}}^{(k)}(f)$$

Where:
$N_{\mathrm{CBN}}(f)$ is the power spectral density of the colored background noise,
$N_{\mathrm{NN}}(f)$ the power spectral density of the narrowband noise,
$N^{k}_{\mathrm{NN}}(f)$ is the power spectral density of the subcomponent k generated by the interferer k of the narrowband noise.

The noise types explained in section 2.1 are, on the contrary, varying in time span of milliseconds and microseconds, and can be gathered in one noise class called “impulsive noise”, pointed out also in other literatures as “impulse noise” [Sartenaer04]. Because of its relatively higher amplitudes, impulse noise is considered the main cause of burst error occurrence in data transmitted over the high frequencies of the PLC medium. The impulsive noise class is composed of the periodic impulses that are synchronous with the main frequency and the asynchronous impulsive noise. [Hrasnica *et al* 04] asserts that one approach to model these impulses is a pulse train as in equation (2.2.A).

$$n_{\mathrm{imp}}(t) = \sum_{i=-\infty}^{\infty} A_i \cdot p\left(\frac{t - t_{\mathrm{a,i}}}{t_{\mathrm{w,i}}}\right) \tag{2.2.A}$$

Where:
t_w is the pulse width,
A is the pulse amplitude,
t_a is the interarrival time,
$p(t/t_w)$ is the generalized pulse function with unit amplitude,
t_w impulse width

Under these noises, the actual capacity of a channel is theoretically derived from Shannon equation (2.2.B) which is,

$$\mathbf{C} = \mathbf{BD} \times \log_2 (1 + S/N), \text{ (shannon-hartley)} \tag{2.2.B}$$

Where:
C the theoretical max capacity of a channel (achievable under noise) (bps)
BD is the bandwidth of the media (Hz).

The powerline channel presents hostile properties for communications signal transmission, such as noise, among others but besides noise effect, any electromagnetic signal has natural strength attenuation due to electrical resistance of the media. Initial signal amplitude, type (analog or digital) and the signal frequency of the signal will determine the level attenuation. Frequency range might also be losing signal energy by radiation energy out of the media and create interference to other communication system. The choice of the modulation technique for a given communications system strongly depends on the nature and the characteristics of the medium on which it has to operate as will be highlighted in the following section.

2.2 Signal Modulation Techniques

It is worthy at this stage to mention that transmission ranges and data rates in a PLC network are reduced and sensitivity to disturbances is increased due to the characteristics of the PLC transmission channel such as large and frequency-dependent attenuation, time-variant impedance, fading and unfavorable noise conditions and variation of noise sources due to different devices connected to the network [Anatory *et al* 06]. So PLC systems take advantage of efficient modulation [Mohamad06], [Hrasnica *et al* 04]. Modulation is a technique that enables information to be transferred as changes in an information carrying signal. Modulation is used both for analog and digital information, in the case of analog information it is affected in soft transitions. In the case of digital information it is affected step by step following signal elements [Zuberi03]. Modulation exists in different forms namely, amplitude, frequency, frequency-shift, amplitude shift keying modulation among others and these different forms of modulation are dealt with in the section below.

2.2.1 Amplitude Modulation (AM)

Amplitude Modulation is the simplest form of modulation. The amplitude of the carrier wave is varied in accordance with some characteristic of the modulating signal which may be analog or digital [Zuberi03]. The following equation represents AM signal:

$$s(\mathrm{t}) = \mathrm{A_c}\,[\,1 + m(\mathrm{t})\,]\cos \omega_c\, \mathrm{t} \tag{2.3}$$

Where:
m(t) is the modulating signal
A_c is the constant, specify power level

2.2.2 Frequency Modulation (FM)

Frequency Modulation is used for broadcasting on the FM band (hence the term FM), the sound channel for TV and certain mobile communication systems. Phase modulation and frequency are special cases of angle-modulation signaling [Sartenaer04], [Zuberi03]. An angle-modulated signal is represented by:

$$s(\mathrm{t}) = \mathrm{A_c} \cos [\, \omega_c \mathrm{t} + \theta(\mathrm{t}) \,] \tag{2.4}$$

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

$$\theta(\mathrm{t}) = \mathrm{D_p}\, m(\mathrm{t}) \tag{2.5}$$

Where:
m(t) is the modulating signal
Dp is the phase-sensitivity of the phase modulator

For FM the phase is proportional to the integral of ***m*(t):**

$$\theta(\mathrm{t}) = \mathrm{D_f} \int_{-\infty}^{\mathrm{t}} m(\sigma)\, d\sigma \tag{2.6}$$

Where:
D_f is the frequency deviation constant

The reason for calling it frequency modulation lies in the fact that the instantaneous frequency varies about the assigned carrier frequency directly proportional to the modulating signal *m*(t).

2.2.3 Frequency-Shift Keying (FSK)

Another name for phase-shift modulation is phase-shift keying (PSK) [Hrasnica *et al* 04]. In phase-shift modulation the phase is shifted differentially relative to the previous phase (for example $+90^0$ and $+270^0$ for bit 1) or absolutely in which case each modulation state is represented by a specific phase (0^0 for bit 0 and $+180^0$ for bit 1) relative to a nominal phase. The differential variant permits less complicated demodulation equipment and is therefore more common. Frequency-shift modulation is also called frequency-shift keying (FSK) also uses the similar shift scheme to vary frequency.

2.2.4 On-Off keying (OOK)

On-Off keying (OOK) is a form of AM signal and is therefore sometimes also called Amplitude Shift Keying (ASK). The approach is to let the carrier wave represent a binary one and no carrier represents a binary zero [Hrasnica *et al* 04]. Since OOK is an AM-type signaling, the required bandwidth of an OOK signal is 2 times the bit rate. That is, the transmission bandwidth B_t of the OOK signal is $B_t = 2B$ where B is the bandwidth of the modulated signal.

2.2.5 Quadrature Amplitude Modulation (QAM)

Quadrature Amplitude Modulation (QAM) is a combination of modulations. In many cases the basic methods of amplitude-shift, phase-shift and frequency shift modulation are combined [Zuberi03]. The combination of amplitude-shift modulation and phase-shift modulation is called Quadrature amplitude modulation [Hrasnica *et al* 04]. This combination permits more bits per hertz than the methods are capable of transmit separately. The general QAM signal is defined as:

$$s(\mathrm{t}) = x(\mathrm{t}) \cos \omega_c \mathrm{t} - y(\mathrm{t}) \sin \omega_c \mathrm{t} \tag{2.7}$$

2.2.6 Orthogonal Frequency Division Multiplexing (OFDM)

Orthogonal Frequency Division Multiplexing is a special form of Multi Carrier Modulation with densely spaced subcarriers and overlapping spectra. To allow an error-free reception of OFDM signals, the subcarriers' waveforms are chosen to be orthogonal to each other [Sartenaer04], [Zuberi03]. OFDM transmits symbols that have relatively long time duration, but a narrow bandwidth. In spite of its robustness against frequency selectivity, which is seen as an advantage of OFDM, any time-varying character of the channel is known to pose limits to the system performance. Time variations are known to deteriorate the orthogonality of the subcarriers. The insertion of the appropriate cyclically extended guard time eliminates interference in a linear dispersive channel; however, this introduces also a loss in the signal-to-noise ratio (SNR) and an increase of needed bandwidth [Hrasnica *et al* 04]. The SNR loss is given by equation (2.8).

$$\mathrm{SNR}_{\mathrm{loss}}(\mathrm{dB}) = 10\log\frac{T}{T - T_{\mathrm{CP}}} \tag{2.8}$$

Where:
T is the OFDM symbol duration
T_{CP} is the cyclic prefix period.

According to the basic OFDM realization, the transmitted signal *s(t)* can be expressed by equation (2.9).

$$s(t) = \sum_{k=0}^{N-1}\sum_{l=-\infty}^{\infty} b_l[k]\psi_k(t - lT) \tag{2.9}$$

Where:
N is the subcarrier frequencies which are then frequency division multiplexed
T in this phase is the OFDM symbol duration.

2.2.7 Direct Sequence Spread Spectrum (DSSS)

Direct Sequence Spread Spectrum (DSSS) is the most applied form of the spread spectrum in several communications systems [Zuberi03]. The principal of direct sequence spread spectrum is to spread the signal on a larger frequency band by multiplexing it with a signature. The system works over a fixed channel. To spread the signal each bit of the packet to be transmitted is premodulated by a code. At the receiver the original signal is recovered by receiving the whole spread channel and demodulated by the same code [Sartenaer04]. In other words, to spread the spectrum of the transmitted information signal, the DSSS modulates the data signal by a high rate pseudorandom sequence of phase modulated pulses before mixing the signal up to the carrier frequency (fc) of the transmission system. The transmitted signal *s (t)* can be written as [Hrasnica *et al* 04]:

$$s(t) = \sqrt{\frac{2E_{\mathrm{b}}}{T_{\mathrm{b}}}}\cos(2\pi f_{\mathrm{c}}t)b(t)c(t) \tag{2.10}$$

Where the data signal *b(t)* is defined as

$$b(t) = \sum_{n=-\infty}^{\infty} b[n] \prod_{T_b}(t - nT_b) \qquad (2.11)$$

Where:
E_b is the energy per information bit,
$1/T_b$ has a symbol rate,
$\prod_{Tb}$ (t) is the pulse train
b[n] is the information bit stream

The wave form of the spreading code, which is a base band signal, is defined by:

$$c(t) = \sum_{m=-\infty}^{\infty} c[m] \prod_{T_c}(t - mT_c) \qquad (2.12)$$

Where:
$\prod_T(t)$ denotes a unit amplitude rectangular pulse with a duration of T
c[m] is the code sequence.

2.2.8 Frequency Hopping Spread Spectrum (FHSS)

FHSS uses a set of narrow band channels and go through all of them in a sequence. This explains the reason why it hops from frequency to frequency over a wide band. The specific order in which frequencies are occupied is a function of a code of sequence and the rate of hopping from one frequency to another is a function of the information rate [Zuberi03]. The transmitted spectrum of a frequency hopping signal is quite different from that of a direct sequence system.

In the FHSS the signal frequency is constant for specified time duration, referred to as a time chip. The transmission frequencies are then changed periodically. Usually, the available band is divided into non-overlapping frequency “bins” [Hrasnica *et al* 04]. The data signal occupies one and only one bin for a specified duration and hops to another bin afterward. According to the generated pseudorandom sequence code, the frequency synthesizer generates a signal with a frequency among a predefined set of possible frequencies, which has to carry the base band signal over the transmission channel [Hrasnica *et al* 04]. The data signal can be expressed as in equation (2.13)

$$b(t) = \sqrt{2P} \cdot \sum_{n=-\infty}^{\infty} \prod_{T_b} (t - nT_b) \cos(2\pi f_n t + \phi_n) \tag{2.13}$$

Where:
T_b is time period
P is the average transmitted power

2.3 Error Handling

PLC networks operate with a signal power that has to be below a limit defined by the regulatory bodies. On the other hand, the signal level has to keep data transmission over PLC medium possible. This means that, there should be a certain signal- to-noise ratio (SNR) level in the network making communications possible [Mohamad06]. As long as the SNR is sufficient to avoid the disturbances in the network, the error handling mechanisms do not have to act. For example, if the SNR is sufficient to avoid an influence of the background noise in a PLC network**.** From [Zuberi03] SNR is a key parameter when estimating the performance of a communications system. This parameter is related to the performance of a communications system. The higher the SNR the better is the communication. SNR is expressed in dB as:

$$\text{SNR} = 10 \text{ x } \log_{10}(\text{Signal Power / Noise Power}) \tag{2.14}$$

More difficulties in PLC transmission systems are caused by impulsive noise, which has much higher power than the background noise as explained previously in section 2.1. In this case, the SNR is not enough to overcome the disturbances and the resulting transmission errors. If the noise impulses are longer, additional mechanisms for error handling have to be applied. In this case, the transmission systems are able to manage damaged bits and correct the data contents [Hrasnica *et al* 04]. The usage of the error handling mechanisms gives rise to an overhead, which takes a portion of the network transmission capacity. We present an overview of currently considered error handling mechanisms for PLC such as Forward Error Correction and Automatic Repeat-reQuest and these are explained in the following sections.

2.3.1 Forward Error Correction

Forward Error Correction (FEC) is a widely used method to improve the connection quality in digital communications and storage systems. The word forward in conjunction with error correction means the correction of transmission errors at the receiver side without needing any additional information from the transmitter [Watson *et al* 07]. The main concept of FEC is to add a certain amount of redundancy to the information to be transmitted, which can be exploited by the receiver to correct transmission errors due to channel distortion and noise. FEC in mathematical theory of communication has a theoretical maximum capacity, which depends on the bandwidth and the signal-to-noise-ratio (SNR), as formulated by equation (2.15) [Hrasnica *et al* 04]

$$R \leq B \cdot \log_2 \left(1 + \frac{P}{N_0 B}\right) \tag{2.15}$$

Where:
R is the communication bit rate in bps.
B represents the channel bandwidth in hertz,
N_0 is the power spectral density of the noise, watt/hertz,
P is the transmitted power, in watt.

The capacity of implemented systems is mostly much smaller than the maximum possible value calculated by the theory. For this reason, the use of suitable codes has to allow further improvement in bandwidth efficiency**.**

2.3.2 Interleaving

A common method to reduce the “burstiness” of the channel error is the interleaving, which can be applied to single bits or symbols to a given number of bits. Interleaving is the procedure which orders the symbols in a different way before transmitting them over the physical medium [Hrasnica *et al* 04]. At the receiver side, where the symbols are de-interleaved, if an error burst has occurred during the transmission, the subsequent flawed symbols will be spread out over several code words. Suffering from disturbances, two adjacent elements of the transmitted symbol are destroyed, building a burst with the length of two elements. In the receiver, the received symbols are de-interleaved, and therefore the error burst is decomposed into two single element errors.

2.3.3 Automatic Repeat-reQuest (ARQ) Mechanisms

ARQ provides a signaling procedure between a transmitter and a receiver. The receiver confirms a data unit by a positive acknowledgement (ACK), if it is received without errors. A request for the retransmission of a data unit can be carried out by the receiver with a negative acknowledgement (NAK), in the case in which the data unit is not correctly received, or is missing [Hrasnica *et al* 04], [Zimmer *et al* 00]. An acknowledgement is transmitted over a so-called reverse channel, which is also used for data transmission in the opposite direction. Usually, an acknowledgement is transmitted together with the data units carrying the payload information. The following section explains three basic variants of ARQ mechanisms.

2.3.3.1 Send-and-Wait ARQ

In accordance with the Send-and-Wait ARQ, after a transmitter sent a data unit it waits for an acknowledgement before it sends the next data unit. If the received acknowledgement was positive (ACK), the transmitter proceeds with transmission of the next data unit [Fair *et al* 02]. On the other hand, if the acknowledgement was negative, the transmitter repeats the same data unit. It can be recognized that this variant of ARQ mechanism is not effective. Especially, in the case of long propagation delays and small data units, data throughput seems to be low [Hrasnica *et al* 04]. The data throughput S for the Send-and-Wait mechanism can be calculated according to the following equation (2.16):

$$S = \frac{n \cdot (1 - DER)}{n + c \cdot v} \tag{2.16}$$

Where:
n is the length of a data unit, in bits,
DER is the Error Ratio of Data units,
c is delay between end of transmission of last data unit and start of the next data unit
v is the transmission rate, in bps.

Therefore too high transmission rate and high delay impact negatively on the throughput and the link utilization is poor. It is also possible that a data unit never arrives at the receiver (for instance, it is lost because of hard disturbance conditions). In this case, the transmitter would wait for an infinite time for either a positive or a negative acknowledgement to transmit the next data unit or to repeat the same one [Hrasnica *et al* 04]. To avoid this situation, a timer is provided within the transmitter to initiate a retransmission without receiving any acknowledgement. So, if the receiver does not receive a data unit and accordingly does not react with either ACK or NAK, the transmitter will retransmit the data unit after a defined time-out.

2.3.3.2 Go-back-N ARQ Mechanism

As was mentioned above, the limitation of the Send-and-Wait ARQ protocol is possibly long transmission gaps between two adjacent data units. To improve the weak data throughput, Go-back-N ARQ mechanism provides transmission and acknowledgement of multiple data units ensuring a near to continuous data flow between the transmitter and receiver [Fair *et al* 02], [Hrasnica *et al* 04]. Thus, a transmitter can send a number of data units one after the other and receives an acknowledgement for the number of sent data units. According to the Go-back-N principle, the transmitter sends the data units without waiting for the acknowledgement from the receiver. The maximum number of data units which can be sent without confirmation is specified by the transmission window. After the transmitted units arrive, the receiver sends acknowledgement for all received data units. If the transmitter receives a negative acknowledgement for a data unit, it has to repeat all data units with higher sequence numbers [Hrasnica *et al* 04]. For this reason, the transmitter requires a sufficient buffer to keep all data units until they are acknowledged by the receiver. Data throughput S is improved when using Go-back-N, than with Send-and-Wait and equation (2.16) becomes equation (2.17)**:**

$$S = \frac{n \cdot (1 - DER)}{n + DER \cdot c \cdot v} \tag{2.17}$$

Where:
n is the length of a data unit, in bits,
DER is the Error Ratio of Data units,
c is delay between end of transmission of last data unit and start of the next data unit
v is the transmission rate, in bps.

2.3.3.3 Selective-Reject

A further improvement of the ARQ efficiency is ensured by the Selective-Reject mechanism. In this case, negative acknowledgements are sent for data units that are missing or disturbed, such as in Go-back-N mechanism [Fair *et al* 02]. However, opposite to the Go-back-N ARQ, the transmitter repeats only the requested data units. Other data units with higher sequence number are considered as correctly received and they are not retransmitted. Thus, the Selective-Reject mechanism achieves better data throughput, as expressed by the following equation (2.18) [Hrasnica *et al* 04].

$$S = 1 - DER \tag{2.18}$$

For the realization of the Selective-Reject mechanism, it is necessary that the receiver buffer is large enough to store the data units until the data units with lower sequence numbers arrive at the receiver. The transmitter can remove data units from the buffer after it receives an acknowledgement, such as in the Go-back-N mechanism.

Combined effects of frequency-dependent attenuation, changing impedance and fading as well as a strong influence of noise characterize power supply networks [Anatory *et al* 06]. As a consequence, it reduces network distances and data rates, and also increases sensitivity to disturbances. For a given communication link the relationship between delay, usually the RTT and the available bandwidth needs to be satisfied using the following equation (2.19), that expresses the amount of bits in transit a given link may contain, under an acceptable delay, as used in Ethernet or high speed network design.

$$\textbf{Bandwidth x Delay = Constant} \tag{2.19}$$

Link delay is proportional to inter-node distance when any other factors like processing time, size of packet, data rate remaining unchanged. So this equation (2.19) will also determine scalability of a link or network and inter-repeater distance for a given PLC sender and receiver devices. To reduce the negative impact of powerline transmission medium, PLC systems apply efficient modulation techniques, such as spread spectrum and OFDM. The problem of disturbances can be solved by well-known error-handling mechanisms such as FEC as explained in the previous sections. Broadband PLC can be applied to HV, MV and LV supply networks as well as within buildings. In the next section 2.4 we review the implementation case studies of these PLC networks inside and outside of South Africa.

2.4 PowerLine Trial and Commercial Deployments in Broadband Economies

2.4.1 Spain

2.4.1.1 Iberdrola PowerLine Communication Trial in Madrid

Iberdrola is one of the leading electrical utilities in the PLC world. It is one of the leading largest electrical utilities in Spain with more than 16 million customers and over nine million of those costumers are located in Spain. Iberdrola owns a very powerful telecommunications network, which is one of the revenue sources of the company [Litttle02]. In 2001, Iberdrola performed a massive PLC deployment trial. It was carried out with objectives to test all the available PLC technologies with their PLC services such as Internet access and VoIP. In addition, the PLC deployment was undertaken with the objective to discover all the relevant aspects regarding electrical grid information and topologies, which could have an effect over the overall performance of PLC. This led to the development of a basic scenario that encompassed technology selection, definition of processes in the different aspects of the service-area selection, installation, maintenance and commercialization. This granted a smooth path towards a commercial deployment of PLC in Iberdrola [Lopez04]. Iberdrola trial deployed the PLC technology in Madrid, since that is where several hundreds of its customers are concentrated. More than four thousand electricity customers were contacted for the PLC trial and more than sixty medium voltages (MV) to low voltage (LV) substations, with their different MV and LV grid were analyzed. Several auxiliary transmission technologies were tested, as a way of carrying the PLC signals from customer homes to the Internet Service Provider (ISP). Three completely different PLC technologies were used in the Iberdrola PLC trial and these were provided by a total of eight different system manufacturers. And through them high speed Internet access and VoIP services were provided [Gomez05].

Conclusions derived from PLC trial by Iberdrola were that the PLC technologies were lacking some degree of industrialization, and in some cases needed adaptation to Spanish regulatory environment. Of note is that the problems presumed for PLC technology regarding conducted and radiated emissions were never detected as a problem, neither for the Spanish Administration nor for complaints in any of the deployed cases. As many as three measurement campaigns were carried out over the deployed PLC trial network, one of them was directly conducted by the Spanish Ministry of Science and Technology [Sendin05].

2.4.1.2 Broadband PLC Commercial Deployment by Iberdrola in Madrid

After the trial, the commercial deployment was eventually agreed upon in June 2003, with the target of launching commercial activities on September 1, 2003 which commenced on 15 October of 2003. Several immediate actions were needed for instance asking for an extension of the license that allowed Iberdrola to offer PLC telecommunication services and how to cope with the services offered by the PLC technology [Little04]. In the first phase of the commercial rollout, only Internet service was implemented. Together with the deployment of the PLC auxiliary network, including the required MV PLC links, between transformer substations. Before that, Iberdrola selected the geographical areas in which the service could be offered before the end of the year 2003 and prepared the entire PLC commercial and marketing issues [Malaysia05].

To solve the area selection aspects Iberdrola developed a software tool that was in charge of selecting the most convenient zones for PLC deployment in different Spanish cities. With this tool, Mirasierra and Ciudad de los Periodistas were the areas firstly selected for the deployment by the end of 2003 in Madrid. This was done by taking into account the number of electrical customers in the area, the total amount of PLC potential contracts added up to around seven thousand distributed in twenty five transformer substations. Preliminary estimations gave the idea that a 10 percent of the electrical customers could be willing to have PLC Internet access of which this covered the target [Gomez05].

In the commercial scenario, the PLC products Iberdrola is offering to its customers in the previously mentioned areas are two, namely, PLC300 and PLC1000. The philosophy behind both these PLC technologies is offering more broadband than the competing technologies, at a lesser price [Little04]. PLC300 competes with dial up connections, offering a higher speed of up to 300 kbps in each direction, upstream and downstream for approximately the same price. PLC1000 offers up to 1 Mbps upstream, and up to 1 Mbps downstream, with a tariff competing against ADSL tariff for the 512 / 128 kbps service. These products were deployed accompanied by an attractive web space of 10 megabytes and five email accounts of 25 megabytes each for the customer. For Internet connection, the PLC modem was lent to the client at zero cost, and the installation was completely free. All this together creates one of the most attractive options for Internet access now in the Spanish market with 95 thousand homes passed (eligible for PLC deployment) and with 4 thousand customers [Sendin05].

Iberdrola continues to deploy even today on a commercial basis, which has been taken place since year 2003. In October 2004, the PLC service was made available to Madrid and Valencia cities, and PLC will spread to more main cities in Spain. Up to 60 thousand households had the PLC signal made available in October 2004. It reached a rate of 150 thousand households with PLC signal in the customer meters rooms yearly. Iberdrola is successfully offering two different Internet access services up to 600 Kb symmetric for a price of 39€ [Sendin05]. At the end of October 2004 new services were made available up to 1 Mb as a way to continue offering a highly competitive service to the market. In its deployment, Iberdrola pursues a retail business model and expects to commercialize PLC under Iberdrola brand. Iberdrola is working with and deploying both MV and LV PLC using the current available technology. Iberdrola has carried out some interference tests on its commercial PLC network that showed again as before that the deployed PLC caused no interferences. The future steps for Iberdrola are to further PLC deployment to other Spanish regions, launching a VoPLC service and start to use the PLC equipment for some electrical core business activities such as meter reading [Little04].

2.4.1.3 PowerLine Communication Deployment Trials by Endesa

Endesa Net Factory (ENF) is a subsidiary company of Endesa Group. Endesa is one of the largest private utility companies in the world, with more than 20.5 million customers around 12 countries. Endesa has been active for the last six years in PLC activities, launching pilot trials, doing business analysis, launching a massive trial and keeping institutional relationships [Marie *et al* 05]. Endesa has been testing and working on the development of PLC technology, which allows transmitting telecommunication services through MV and LV electrical power grids. Endesa has gained a deep PLC technological expertise through PLC pilot trials such as the Zaragoza Massive PLC Technological Trial (MTT). Since year 2000 Endesa has carried out various field trials in four different cities, which are Barcelona, Zaragoza and Sevilla in Spain, and Santiago de Chile in Chile [Alfonsin03] as will be discussed below.

2.4.1.4 Barcelona PowerLine Communication Deployment Trial

Endesa led the way for the PLC technology in Spain and started the development of PLC activities through its Proyecto PLC. At the beginning of 2000 PLC pilot trial was started, in Barcelona using Ascom PLC technology. The Barcelona PLC pilot trial was deployed for one and half years with 25 users in two buildings connected to the same substation [Alfonsin03], [Marie *et al* 05]. Within a space of a year, about 25 users had broadband Internet access and telephony over IP delivered to them through PLC technology at 5Mbps. The PLC trial results were promising and depicted that PLC technology is viable and supports provision of broadband services over IP. In addition, trial measurements on interference showed that the intensity of PLC electromagnetic waves was in conjunction with both national and FCC 15 requirements on safety [Little02]. On February 2004, commercial activities were launched in Barcelona initially covering a market of up to 10 thousand households. Endesa, together with AUNA (Telecom Operator), launched commercial activities in some areas of Barcelona in February 2004[Guerin *et al* 03].

2.4.1.5 Sevilla PowerLine Communication Deployment Trial

In January 2000, PLC Endesa deployed another pilot trial in Sevilla using the DS2 PLC technology [Alfonsin04], and the deployment progressed for a period of a year with users having the same conditions and services as those deployed in Barcelona [Garriogosa05]. The DS2 PLC technology was tested with 25 final users with broadband Internet connection reaching speeds of up to 12 Mbps. The services tested were telephony over IP (VoIP) and broadband Internet access [Marie *et al* 05]. Another technical trial with similar characteristics to the Barcelona and Sevilla PLC trials started in Santiago de Chile in April

2002 [Little02].

2.4.1.6 Zaragoza PowerLine Communication Deployment Trial

The largest PLC trial to be performed to date has been in the city of Zaragoza and it has become an international reference, mainly due to the development of MV PLC and the massive use of VoIP [Alfonsin04]. In September 2001, Endesa began the PLC trial regarded as the Massive Technology Trial (MTT) in Zaragoza for a duration of two years [Guerin *et al* 03]. This was the first world experience using the PLC technology in MV and VoIP over PLC at great scale [Marie *et al* 05]. Endesa successfully launched this larger scale PLC trial in Zaragoza aiming at identifying the main issues surrounding the technology and its deployment as well as studying its viability on an operator scale. Starting in April Endesa deployed a PLC telecommunications network, providing broadband Internet and telephony to more than 300 buildings connected through 140 transformer stations. Endesa connected more than 800 users in May and the number increased to over 2 thousand users by September of the same year [Alfonsin04], [Little02], [Marie *et al* 05].

The services provided were broadband Internet access and VoIP. These facilities were deployed and offered for free of charge during the trial period. The PLC technology deployed for the Massive Technology Trial in Zaragoza was Ascom and DS2 technology. Experiencing transmission speeds of up to 45Mbps [Marie *et al* 05]. In the trial, the MV network was used for data transmission and it comprised DS2 technology. The network designed for the trial had 82 MV PLC links and aimed at proving that MV PLC is a technical solution with important advantages compared to other transmission technologies. The Ministry of Science and Technology of Spain partly funded the project, indicating the importance of the PLC technology as a key instrument to boost the development of the Spanish Information Society [Little02].

2.4.1.7 PLC Commercial Deployment by Endesa in Zaragoza

The Zaragoza PLC trial was finished in December 2003, following satisfactory results from the trial, Endesa started commercializing Internet access and Voice over IP services [Guerin *et al* 03]. Endesa, together with AUNA (Telecom Operator), launched commercial activities in some areas of Zaragoza in October 2004. The main features of PLC network in the city of Zaragoza include Voice over IP and Internet access services being provided to users. The commercial offer was available to a specific group of customers. The objective was first to analyze and validate the commercial viability of the PLC services [Marie *et al* 05]. Zaragoza is a worldwide reference because of its MV PLC which boasts of over 200 PLC links. 20 thousand households already have PLC signals in their meter rooms and with over 2 thousand PLC users. After having obtained the operating license from the Spanish regulatory authorities, Endesa started, operating also as a carrier's carrier for other telecom operators. About 60 percent of users contracted for the PLC commercial services offered by Endesa. The penetration rate of PLC in the selected areas is higher than ADSL average penetration in Spain. This is supported by the fact that over 85 percent customers of Endesa signed for PLC VoIP services. The next step in Endesa PLC project is analyzing the commercialization results and areas for future PLC deployments [Little04].

2.4.1.8 General Design of the Zaragoza PLC Network by Endesa

The general design of the Zaragoza network comprise a city point of presence (POP) connected to MAN POPs with dark fiber and Gigabit Ethernet switches deployed on the distribution network first level. On the second level, only MV links are used to join MV substations, sometimes in rings or sometimes in branches. Voice Internet and carriers connections are located in the city POP. There also exist MV rings, with Spanning Tree Protocol running as redundant protocol, in order to provide high availability. Manufacturers Mitsubishi and Sumitomo provide all PLC equipments on the Endesa network [Guerin *et al* 03]. However, one part of the Zaragoza network has been assigned to research and development. The users developed an intense usage of PLC services. In that regard, Endesa deployed some video on demand (VoD) services with some specific friendly customers in the research and development area of Endesa [Marie *et al* 05].

2.4.1.9 Video Services on Demand over PLC Experiences of Endesa

Endesa has selected a specific area in Zaragoza to be used for research and development activities. The area has a mix of different electric topologies, concentration of test-bed users and interesting conditions such as different materials and kind of transformer substations [Arriola05]. Between the test bed users selected Endesa provided some of them were with "Triple Play" services. The users enjoyed a broadband Internet connection speed of 9 Mbps, VoIP access (national, international and mobile calls) and VoD services. For PLC VoD three initiatives were done. Access to a video server to watch some films allocated there on request from the "movie library", access to some contents allocated in a "content server" such as documental, recorded magazines, news summary, and access to real television channels [Marie *et al* 05].

It is necessary to say than more than 30 users were tested free of charge and the "Triple Play" services were done without any incident. At the same time, the OPERA standard demonstrated to offer the appropriate features and quality of service (QoS) level to fulfill the requirements of the services. The OPERA Standard was able to provide "Triple Play" services thanks to its high bandwidth rate of 200 Mbps and the advanced QoS services. OPERA Standard allowed having a broadband internet access at a speed of 5 Mbps, a VoIP call and a VoD application throughout the same CPE at the same time in a commercial environment [Marie *et al* 05].

2.4.2 German

2.4.2.1 Münchner Verkehrsverbund PLC Trial in Manheim

PowerPlus Communications (PPC) helped plan and build six commercial PLC deployments in Europe, five in Germany and one in Austria [Malaysia05]. However, in Europe, Germany has led the way for a more mature PLC technology. In 2000, PLC broadband access was tested successfully by Rheinisch-Westfälische Elektrizitätswerke (RWE) and Energie Baden Wurttemberg AG (EnBW) power companies. The PLC trials covered 400 German households. In July 2001, RWE and Münchner Verkehrsverbund (MVV) launched commercial PLC-based services for the first time in town of Essen and Mannheim respectively [Little02].

Mannheim is about 100 kilometers south of Frankfurt and a few miles Northeast of Heidelberg, not too far from the western border with France [Malaysia05]. MVV has conducted a full commercial rollout in Mannheim after the successful completion of a pilot project. In April 2002, there were 1.5 thousand paying customers for the PLC commercial services. By the end of 2002, the target reached a customer base of 10 thousand subscribers from a potential of 120 thousand households. The company in its PLC deployment used the technology provided by Main.net [Little02]. MVV is using the PLC system for security cameras at its facilities and at some bus stops used by its own transit business [BPL05].

2.4.2.2 PowerLine Communication Deployment by PowerPlus Manheim

PPC is the PLC market leader in Germany with more than 200 thousand households in the PLC coverage area. Power PLUS Communications AG is a joint venture between MVV Energie AG and ABB New Ventures GmbH. MVV Energie AG started on July 1st 2001 in Mannheim with commercial PLC deployment. This commercial deployment has been transferred to PPC. The PLC project by PPC covered different aspects of PLC technology, beginning with pilot trials, commercial launches and PLC services development. All of the PLC deployments used Main.net PLC hardware. Home Plug gear was used in some of the deployments for in-premises networking and each deployment required a unique combination of technologies [BPL05]. PPC network in 2004 covered 90 thousand households with PLC in Mannheim. More than 5 thousand subscribers were deployed with fast Internet access through PLC at speeds of up to 400 kbps. PPC is building up a new business segment, creating a combined solution of PLC and WLAN dedicated to larger networks. PPC offers successfully combined PLC-WLAN solutions for hotels and it has not been proven that there are any interference problems caused by the deployed PLC [Little02]. Power cable installation in Mannheim is 70 percent underground, while the remaining 30 percent is shielded overhead. In addition, Mannheim PLC has been used for setting up a LAN at Willebrand Middle School, in Herten, Germany [BPL05].

2.4.2.3 Second PLC Deployment by PowerPlus in Dresden

The second largest deployment of PPC is in Dresden, formerly the capital of Saxony in East Germany. Its telecom system uses expensive fiber optic network to support digital subscriber line (DSL). Stadtwerke Drewag is the electric utility in Dresden. Stadtwerke means public utility [BPL05]. Drewag started a PLC commercial rollout at the end of 2003. It rolled PLC signal to 25 thousand homes, by the end of 2003, Drewag had about 2 thousand subscribers signed up for the PLC network. In September 2004, Drewag continued deploying adding 15 thousand households and 700 subscribers to its previous 2003 PLC deployment [Little04]. The city of Hameln like Dresden lacks DSL [BPL05]. The local utility Stadtwerke Hameln launched its commercial PLC project at the end of 2003. In September 2004, Stadtwerke Hameln had deployed PLC to 25 thousand households and had reached a thousand subscribers [Little04].

2.4.3 Austria

2.4.3.1 PowerLine Communication Deployment by Tiwag in Tyrol

Tiwag, the leading electricity supply utility in Tyrol, has been long committed to broadband PowerLine Communication systems [Austria06]. Today there are already several hundred users such as schools, SMMEs, hotels and households in selected Tyrolean towns using Internet access via the electricity grid. But with the PLC market launch in broader context, plans are to increase importantly the number of customers connected and using PLC broadband services. In all its PLC deployments, Tiwag used the technology provided by Ascom [Little02].

2.4.3.2 Linz AG PLC Deployment Trial in Raum Linz-Urfahr

Linz AG is an Austrian power utility providing commercial PLC services since autumn 2002. Linz Strom AG begun a PLC commercial rollout in Linz and had 2 thousand users connected by the end of 2002. The PLC project used the Main.net technology. Previously, in April 2001 a pilot project with 20 users was conducted in Raum Linz-Urfahr [Little02]. The main highlights of the rollout are that in September 2004 Linz AG had deployed 37 thousand households with PLC coverage. The deployment included MV and LV PLC systems. Linz AG had about 3 thousand subscribers in September 2004. The PLC broadband Internet access offered in Linz had a speed of 768 kbps. The number of subscribers increased from a thousand to 3 thousand within a time space of a year that is from autumn 2003 to autumn 2004 [Little04]. The unfortunate reality on the Linz PLC trial was that measurements on interference showed that the intensity of PLC electromagnetic waves did not meet with both national and FCC 15 requirements on safety [Austria06].

2.4.3.3 PowerLine Communication Disturbances in the Raum Linz-Urfahr Trial

In Austria, broadband services via PLC are being provided in the Linz region with approximately 250 thousand inhabitants [Little04]. Since the first trials of this technology in this region, which commenced in 2001, the radio amateurs, and various public safety organizations using radio services in the HF band in this region, periodically reported disturbances in the frequency bands below 30 MHz, which were, according to the opinion of the spectrum users, caused by PLC operation in Linz [Austria06]. In order to verify the complaints of the various spectrum users, the competent Austrian authority (the Federal Ministry for Transport, Innovation and Technology, Telecommunications Authority) investigated the reported disturbances. The measurements carried out in May 2004, April 2005 and November 2005 clearly showed that the cause of the disturbance reported by users of the HF band in Linz is the operation of PLC. In particular, the measurement proved that the emission of PLC installations is up to 16000 times (42 dB) higher than the relevant limit [Austria06] so further investigation on causes is needed.

2.4.4 Italy

2.4.4.1 Ente Nazionale Energia Elettrica PLC Trial in Grosseto

Ente Nazionale Energia Elettrica (Enel) started pilot projects in the summer of 2001 in Florence and Bologna, and a commercial trial in January 2002 in Grosseto. The network designed for the market test counts more than 90 MV/LV substations, which are, connected with dedicated data links. Enel deployed the PLC trial using PLC technology provided by

Ascom, Main.net and DS2 companies. More than one thousand buildings were connected via PLC thus reaching more than 6 thousand potential households. In the middle of 2002 there were over 2 thousand users already connected in Grosseto [Little02].

The PLC non-commercial trial deployed by Enel in Grosseto covered 70 thousand inhabitants by the end of 2002. The project involved about 56 percent of the low voltage substations, guaranteeing a potential coverage of 75 percent of all electricity customers. The deployment was realized only on the low voltage network [Napolitano05]. In all, 2.4 thousand users were connected in 950 buildings with the installation of about 3.8 thousand PLC devices. Enel successfully deployed the low voltage PLC network and it then started the PLC MV solutions tests in 2004 in Grosseto. The PLC MV solutions by Enel reached a very quick deployment. All potential users were connected very rapidly with this PLC network. The Enel Company noticed a high level of customer satisfaction in its PLC technological trial [Little04].

It should be highlighted that the strong interests and developments of Enel are in the field of meter reading applications using PLC [Napolitano05]. The stability of the systems and technology during the trial was very high and Enel did not have any problems with electromagnetic interference. In fact, Enel did not detect any particular problem during the operation of the entire system. Neither regulatory nor technological problems constituted uncertainties for Enel in the launch of its PLC project. No authority or any private entity made any official complaint about interferences, although, some associations did ask for information about the PLC tests done by Enel on the PLC trial network [Napolitano05]. In 2004, the Enel PLC project was transferred to Wind, the telecommunications operator owned by Enel. All the future steps and strategic decisions on PLC deployment were taken directly by Wind from then on [Little04].

2.5 Trial and Commercial PowerLine Deployments in Non-Broadband Economies

2.5.1 Ghana

2.5.1.1 Cactel PowerLine Communication Deployment Trial in Accra

Cactel Communications, a United Kingdom-based PowerLine Communications (PLC) company, and Tecnocom, a systems integration company based in Spain, undertook a successful delivery of a PowerLine communications trial in Ghana, Accra, which herald one of the PLC implementation in Africa [Cactel06]. The PLC trial was based on the innovative PLC chip developed by DS2. The deployment trail took place from 20th to 24th June 2005 in Accra the capital city of Ghana. Cactel Communications spearheaded the project, and the PLC network was designed and built by the Spain based Tecnocom Company. The PLC trial was deployed at the premises of Graphic Communications Group Company, a leading media organisation in Ghana. The non-commercial PLC trial was provided with a radio link, which facilitated connectivity between the PLC network and the national communications network of Ghana. The PLC deployment included the testing of various PLC applications such as telephony, Internet access and video surveillance [Ministry06].

In the PLC trial tests, a MV substation was connected to the premises of the Graphic Communication Group, which has its own LV substation. The test took place on the third floor of the building and was set up to power up all the sockets. It was a PLC trial designed to show that the system can work in an African environment. Cactel Communications was able to establish Internet connectivity, VoIP services, live streaming and the use of surveillance cameras through the PLC network [Cactel05]. During the trial, they were able to use Skype to make calls to Europe and to make calls to Ghana Telecom and mobile subscribers on all networks in Ghana. The trial project was able to demonstrate video surveillance and the creation of a telephone network over IP within a building connected with analogue phones [Ministry06].

Cactel Communications aim at providing infrastructural PLC solutions to help offer significantly cheaper access to telephony, data and other telecommunications services across the country of Ghana. The PLC trial received positive responses, to the effect that, when PLC is commercially implemented it would substantially boost the ICT potential of Ghana. The PLC trial generated the arrival of PLC as a business and community development platform to bridge the digital divide. Cactel Communications has ambitions for PLC in Ghana and intends to extend its alliance with Tecnocom of Spain to further PLC rollout to other African countries [Cactel06].

2.5.1.2 Ghana University PowerLine Communications Network Deployment

Following the successful first installation in Accra, Cactel Communications in collaboration with the University of Ghana, Legon, launched another high-speed PLC broadband Internet, telephony and wireless communications project. The PLC pilot harnessed the electricity distribution network to provide last mile connectivity to the student and staff population at the main University campus, Legon [Cactel05]. It provided users with PLC access to Internet, telephony and wireless telecommunication services across three sites on the University of Ghana Legon Campus. The PLC network linked the International Students Hostel, the ICT Directorate and the University Registry Department with a PLC high-speed broadband network offering telephony and multimedia services such as video on demand and remote video surveillance. The PLC network deployed at Ghana University depicted the interoperability of PLC with fibre and wireless networks. Cactel Communications provided a PLC Wi-Fi hotspot in and around the ICT Directorate building at the Ghana University, which was available to anyone with a wireless-enabled laptop. The PLC technology used by Cactel Communications in its deployments is based on the pioneering PLC technology developed by DS2 of Spain, which provides up to 200Mbps of data transfer along existing electricity infrastructure. Tecnocom, a global systems integration company, based in Spain worked again with Cactel Communications in deploying the PLC pilot project at the University of Ghana [Cactel05].

2.5.2 South Africa

2.5.2.1 Tshwane Metropolitan Municipality PowerLine Communications Trial

The City of Tshwane Metropolitan Municipality (CTMM) is leading South Africa with the deployment of an advanced PLC system, supplied by Grintek Telecom since 2003 [Heske06],[PowerNet03]. The technology deployed for Tshwane Metropolitan Municipality is based on DS2 technology. The PLC products are from multinational companies, InovaTech of Australia supplied to Grintek via Cybercom International [PowerNet03]. Owing to leadership of Tshwane Metropolitan Municipality role as the first local organisation to implement the PLC technology, South Africa is considered a significant proponent and player in this rapidly developing PLC global market. The PLC technology is a perfect fit for local needs, which are equally important across Africa and even in more developed countries [Gedye05],[Naidoo07]. The vision of Tshwane Metropolitan Municipality is the provision of improved services to support the development of people and communities, previously limited and denied access to the benefits of broadband. The equipment offered excellent stability and provided bandwidth of up to 45Mbps. The technology was able to deliver analogue voice, multiple IP telephony and broadband data services including multimedia streaming [Newbury *et al* 05]. The Tshwane Metropolitan Municipality was progressive in its PLC technology deployment and actively collaborated with Grintek Telecom throughout 2003 in implementing the project [Kuun03].

The PLC trial by Tshwane Metropolitan Municipality was deployed in Rooiwal north of Tshwane. As part of the PLC pilot project residents of Rooiwal, north of Tshwane, were connected and were able to make free local calls and access broadband Internet via PLC. The current PLC trial in Rooiwal is delivering ADSL broadband and VoIP services via PLC to the primary school, library and town hall, as well as to 130 Rooiwal households. The homes are all connected with a fully-fledged VoIP installation with a 4 Mbps to 6 Mpbs throughput [Heske06]. The Tshwane Metropolitan Municipality delivered ADSL connectivity via its fibre-optic backbone network to the three PLC head-end units in Rooiwal, which converted the signals to the electrical grid of the Tshwane Metropolitan

Municipality. Nine PLC repeaters were installed at various points along the electrical power grid, extracting and amplifying the PLC signal from and to Rooiwal. According to Grintek Telecom, 64 users can access the ADSL connection per head-end unit, which means that 192 users can operate on the PLC network at any given time. According to [Kuun03] by the end of 2003, the PLC network was fully operational and the customer premises equipment modems were distributed out in January of 2004 [Heske06].

The in-house modem in 2004 was retailed at about R2000 and it is a small box that plugs simultaneously into the back of a computer and into an electricity socket. Once plugged the modem, it takes about four minutes to connect to the network. It is then possible to take any analogue phone and plug it into the modem to use it to make VoIP calls [Kuun05]. The modem did the VoIP conversion itself and allowed the Rooiwal residents to make free local calls on the PLC network. When Rooiwal residents needed to make calls outside of the Tshwane Metropolitan Municipality, they connected via telecoms service provider Storm to Telkom. Rooiwal PLC network is connected to the Internet via Telkom through a point of presence (POP) in the City of Tshwane network operating centre, with a fibre optic line of the Tshwane Municipality [Heske06]. The previous PLC pilots in South Africa were very successful, but these had been on a small scale, with only three or four houses. The town of Rooiwal provided the perfect opportunity for South Africa to test the PLC technology on a larger scale as part of its investigation into frequency interference [Gedye05].

One of the most exciting developments is the Rooiwal Broadband Village project where all the houses in this town have been networked with a 4 Mbps PLC broadband connection. These connections are 4 times faster than Telkom DSL offering. The traffic is carried over 28 km on the fiber network of Tshwane Municipality while the last mile connectivity is provided through the existing electrical power cabling (PLC). The full PLC technology has a theoretical capacity of up to 200 Mbps [Kuun03], [Naidoo07]. The Rooiwal users utilize the PLC broadband connections for anything from research to entertainment. This project has proven to be so successful that Tshwane Municipality is now preparing for commercial launch in the East of Pretoria [MyADSL06a]. The process of commercially launching PLC in the Eastern Suburbs of Pretoria is done through a partnership between Goal Technology

Solutions (GTS) and the Tshwane Municipality [MyADSL06b].

2.5.2.2 Tshwane Municipality Proposed PLC Commercial Package by GTS

In 2006 GTS finalized the PLC trial in the Tshwane Municipality region and the PLC results were excellent [Kuun06], [Naidoo07] and GTS announced that it was ready to roll out commercial PLC services in Tshwane. PLC service coverage projected included Tshwane suburbs of Alfen Park, Menlyn Retail Centre, Moreleta Park, Monument Park, Woodhill, Mooikloof and Garsfontein. While GTS is currently focusing on Tshwane, they are also working with other municipalities on possible similar projects. The initial PLC commercial offering which was proposed by GTS was a DSL 512 equivalent service with a 5 GB usage allowance at an all inclusive cost of R479 (R420 ex VAT). This is significantly cheaper than the comparable ADSL offering which cost users over R700. PLC users interested in telephony services on top of their broadband offering will also be able to purchase this service from GTS. GTS projected the basic monthly telephony cost to be just under R 100, while the call costs on average will be around 15 percent cheaper than Telkom rates [MyADSL06b].

2.5.3 PowerLine Communications Deployment Projects Underway in Africa

Goal Technology Solutions (GTS) the broadband service company in South Africa at the time of writing had PLC rollouts under way, one in Durban and the other in Uganda. The Durban Municipality in South Africa has given GTS two real-world PLC pilots to be undertaken on a school and a couple of houses on a street some distance from the mini substation [Southwood06]. The EThekwini (or Durban) Municipality in 2006 promised to launch a PowerLine PLC pilot in the Morningside Berea Park area, promising speeds of 2 Mpbs and higher. EThekwini is the name given to the whole metropolitan area that incorporates the city of Durban and the areas surrounding it [MyADSL06b]. In letters sent out in these regions, residents were invited to participate in the PLC project, and receive free Internet access during the three month trial period. The PLC trial will serve to evaluate the service and establish whether it is feasible to launch a commercial service afterwards in Durban. Should the trial prove to be successful, the PLC service will be rolled out as a commercial offering to the residents of EThekwini [MyADSL06c].

In Uganda GTS is to deploy PLC in a number of Uganda Telecommunications Limited (UTL) office buildings in Kampala [Southwood06]. UTL signed an agreement with GTS to provide PLC solutions on Thursday 28th June 2007. PLC presents an alternative solution to provide communication access to Ugandans in a faster and more convenient way. UTL is in the process of expanding communication access and with PLC broadband to be made available to more Ugandans as long as they have a power connection. The vision of UTL is to provide communication access, with PLC as part of the broadband solution package. Uganda Telecom in collaboration with GTS will install PLC in qualifying areas at no cost to the developers or residents, the end users only pay for the services they need [Uganda07]. In addition, GTS will be rolling out PLC to a number of security estates in South Africa. Further more GTS is looking forward to distributing broadband through setting up PLC in other African countries including DRC and Rwanda [Southwood06]. Implementation of broadband PLC has been underway at Kwame Nkrumah State University in Ghana since 2006. Cactel, a power line communication company, is in the process of implementing a PLC network that would allow staff and members of the Kwame Nkrumah State University community to access the internet through the existing electricity lines [Andam06].

2.6 Conclusion

The chapter has discussed noise, PLC modulation and well-known error-handling mechanisms that PLC utilizes to correct channel impairments present in the PLC environment for the reception of error-free communication signal. While not exhaustive, it has reviewed and acknowledged a number of current PLC case studies inside and outside of South Africa with particular emphasis at constraints and conditions that facilitated and encouraged adoption and application of broadband PLC. However, it has been observed that, broadband PLC in some instances was lacking some degree of industrialization, while in some cases it needed adaptation to the regulatory environment. Of note are the measurements carried out in May 2004, April 2005 and November 2005 in Austria. They clearly showed that the cause of disturbance reported of the HF band in Linz was the operation of broadband PLC. In particular, the measurements proved that the emission of broadband PLC installations was up to 16000 times (42 dB) higher than the relevant limit [Austria06] so further investigation on causes is still needed.

The problems presumed for broadband PLC in Spain regarding conducted and radiated emissions were never detected as a problem in all the deployed cases. As many as three measurement campaigns were carried out one of them was directly conducted by the Spanish Ministry of Science and Technology [Sendin05]. A clear procedure was used to solve the deployment area selection aspects by Iberdrola. It developed a software tool that was in charge of selecting the most convenient zones for broadband PLC deployment in different Spanish cities [Gomez05]. It is vital to note the fact that these projects have been done in different countries with different electrical topologies, because of that there are no clear procedures; in some instances PLC is regarded as good and in others as unviable. Hence, investigation is needed for sound deployment PLC methodologies, to make broadband PLC reach its potential not only in the provision of end services but lower cost, high quality applications to all segments of the economy. In countries like South Africa it has been observed that broadband PLC exhibits potential scope to extend broadband services. The following chapter discusses and proposes how to design and implement broadband PLC deployment methodologies for office and residential electric grids that achieve broadband delivery.

Chapter Three

Designing Broadband PLC Deployment Methodologies

This chapter describe possible PLC methodologies that can be developed for typical medium voltage (MV) and local voltage (LV) PLC networks. The design of broadband PLC networks has demonstrated to require special knowledge about the internal PLC equipment functionality and implementation. The chapter is structured in the following way. The first part is a description of different MV and LV electrical topologies. The second part of the chapter discusses the design requirements, description of PLC communication equipments and how to achieve possible broadband PLC topologies in the MV and LV networks. The chapter ends by presenting proposed MV, LV broadband PLC architecture topologies and LV user requirement PLC methodologies. In this sense, advantages and disadvantages of the each of the proposed broadband PLC topology are explained for both the MV and LV networks.

3.1 Electricity Network Topologies of the Distribution Network

The electricity networks are made up of three categories as regards the voltage level which they transmit excluding the generation voltage level. These stages are transmission, sub-transmission and distribution [Collet03], [Ahola03]. The significance of distribution networks in this research cannot be over emphasized, because much of the research is centered on the distribution networks. These distribution networks are divided into two parts namely medium voltage (MV) and low voltage (LV) distribution networks, also known as primary and secondary distribution networks. The voltages can change depending on the national regulations and the internal procedures of each power utility [Castro *et al* 05], [Vazquez *et al* 05]. The following sections and subsections describe the common electrical topologies, which can be found in the distribution networks (MV and LV networks). The knowledge of these MV and LV electrical grid topologies will provide considerable knowledge that allows better designing, implementation and deployment of the broadband MV and LV PLC network topologies. LV topologies are more bound to geographical and architectural topologies of end-user settings.

3.1.1 Medium Voltage Electricity Network Topologies

The circuitry that the MV networks use to transport the electrical energy is in a structure of double or single circuit. Double circuit or derivation consists of two lines for each phase, one of them acting as the service line and the other acting as a backup line [Collet03]. This is so to avoid overloading the lines and to better enhance responses to possible failures. Double derivation is only present in high density areas or localities with special requirements. The average number of MV/LV transformers on the MV cable is 20 transformers, but this number may vary from 4 to 30 transformers. The distance between two MV/LV transformers on the MV cable can be from 150 to 400 meters [Castro *et al* 05] depending essentially on the current user load density in the area one power line is made of underground cable of 3 to 4 insulated wires for the 3 phases layout or overhead metallic conductor usually of one naked wire.

The other circuitry employed to transmit electrical energy in the MV networks is the single circuit, which consists of one line for each phase. The average number of MV/LV transformers and the distance between two MV/LV transformers on the MV cable is the same as in the double circuit or double derivation system [Campi *et al* 05]. The distance between substations in the low density is longer and can be up to 1000 meters when using the single derivation. These features may slightly vary from one utility to another based on country and professional standard adopted. There are three geographical topologies to deliver electricity at the primary distribution level namely radial, ring and networked topologies [Ahola03] as will be explained in the following sections.

3.1.1.1 Radial Topologies

This topology links together HV/MV electrical substations to the MV/LV substation transformers by means of radial electrical lines as shown in Figure 3.1.

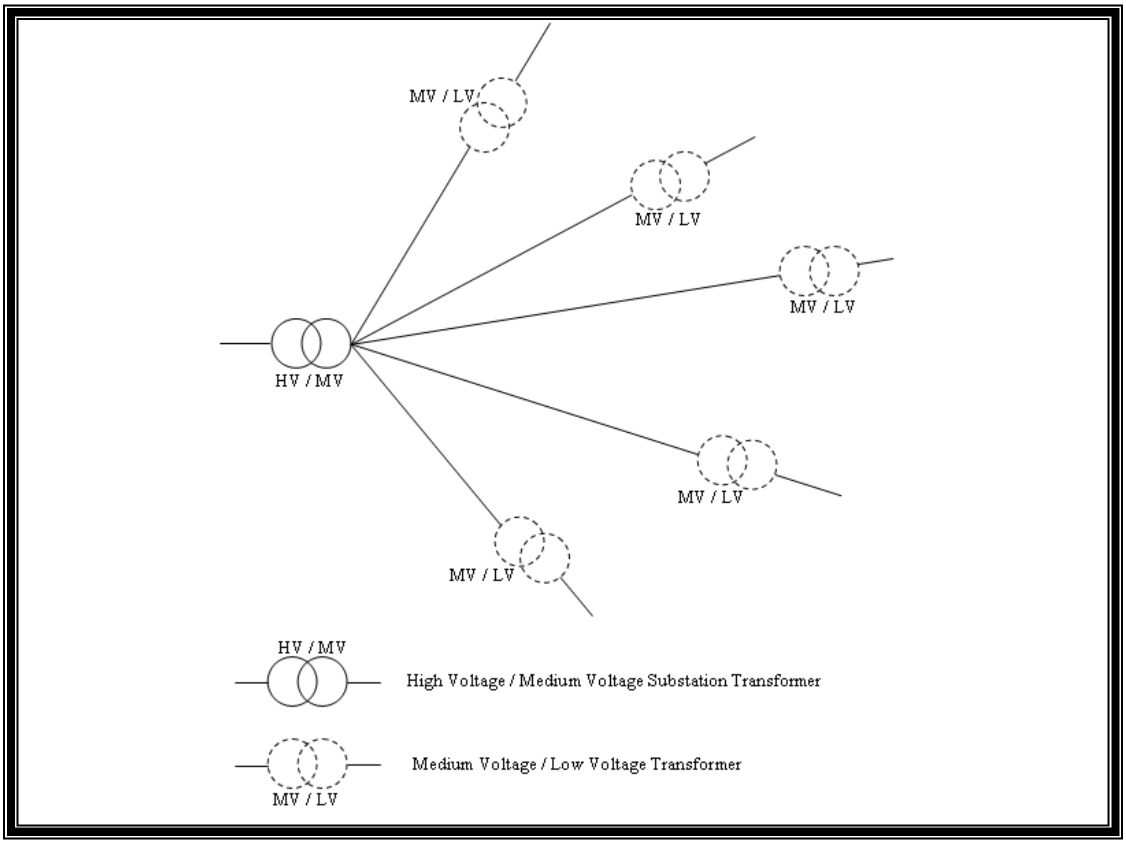

Figure 3.1: Radial Topology with Exclusive MV lines

These electrical lines or feeders can be limited to one substation transformer or can feed several substation transformers. This topology is equivalent to a one-level tree topology. The advantage of the radial system by means of exclusive MV feeders is the centralized control of all the transformer substations. This topology should be thought as similar to a star topology in communication and data transmission network. The structure of the single MV line in Figure 3.2, feeding several substation transformers, passing from one transformer substation to another is very common [Vazquez *et al* 05]. MV/LV transformers fed in this scenario are like connected to a bus topology in Ethernet LAN. Each may be disconnected without splitting MV line in isolated partition. Only the corresponding LV line of the disconnected transformer will get no power. This structure is used to cover long distance areas with intermediate that also require electricity.

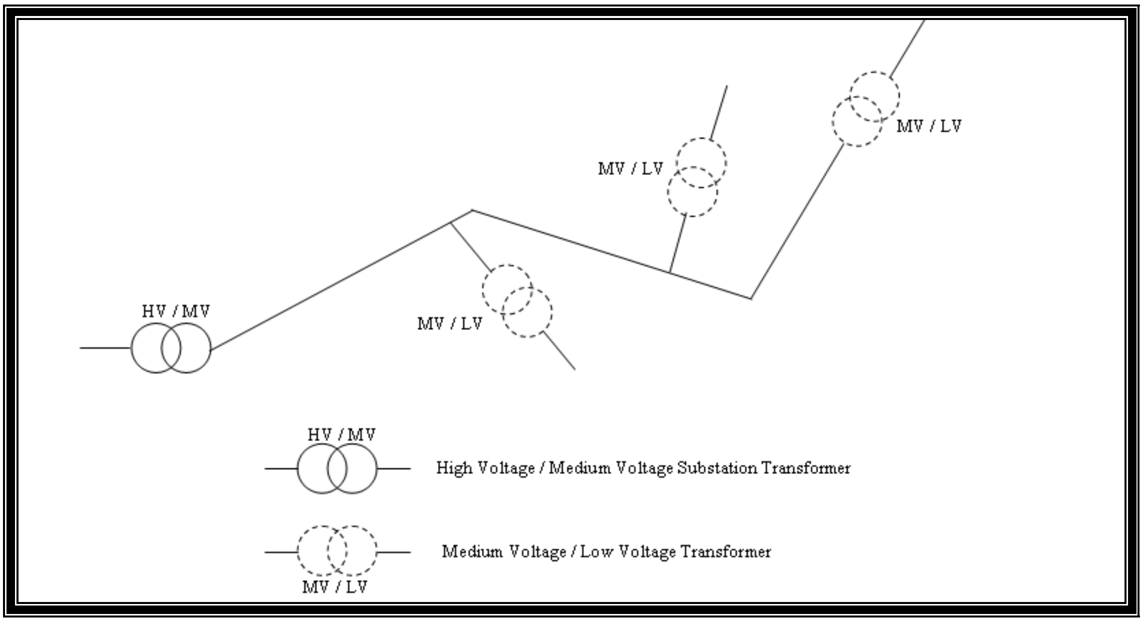

Figure 3.2: Radial Topology with Single MV line

All or part of subsequent MV transformers may also be single transit transformers for example MV/MV whose output voltage level is not yet at LV level suitable to connect end-users consumers. In this scenario disconnecting the transformer will partition the entire MV line into two isolated segments working similarly to an open or broken token bus. If viewed as a tree topology then each transformer occupy a node of the tree and present a common failure for subsequent transformers. Both radial systems in Figure 3.1 and Figure 3.2 are quite intuitive thus implying a simpler design of the network. The tree shaped topology is designed by combining the other two radial systems explained in the previous paragraphs. The line comes from the electrical substation and divides into branches and more branches until reaching the transformer substations [Vazquez *et al* 05]. Figure 3.3 show the sketch of the tree shaped topology where the main substation is feeding a main MV line (main feeder) and several secondary lines (secondary feeders) feeding other MV/LV transformers (substations) are connected to it as branches forming a tree structure. Each branch can be split to other branches and so on, each one feeding one or more substations [Campi *et al* 05]. In this tree-shaped topology all or some subsequent transformers may be of MV/LV type.

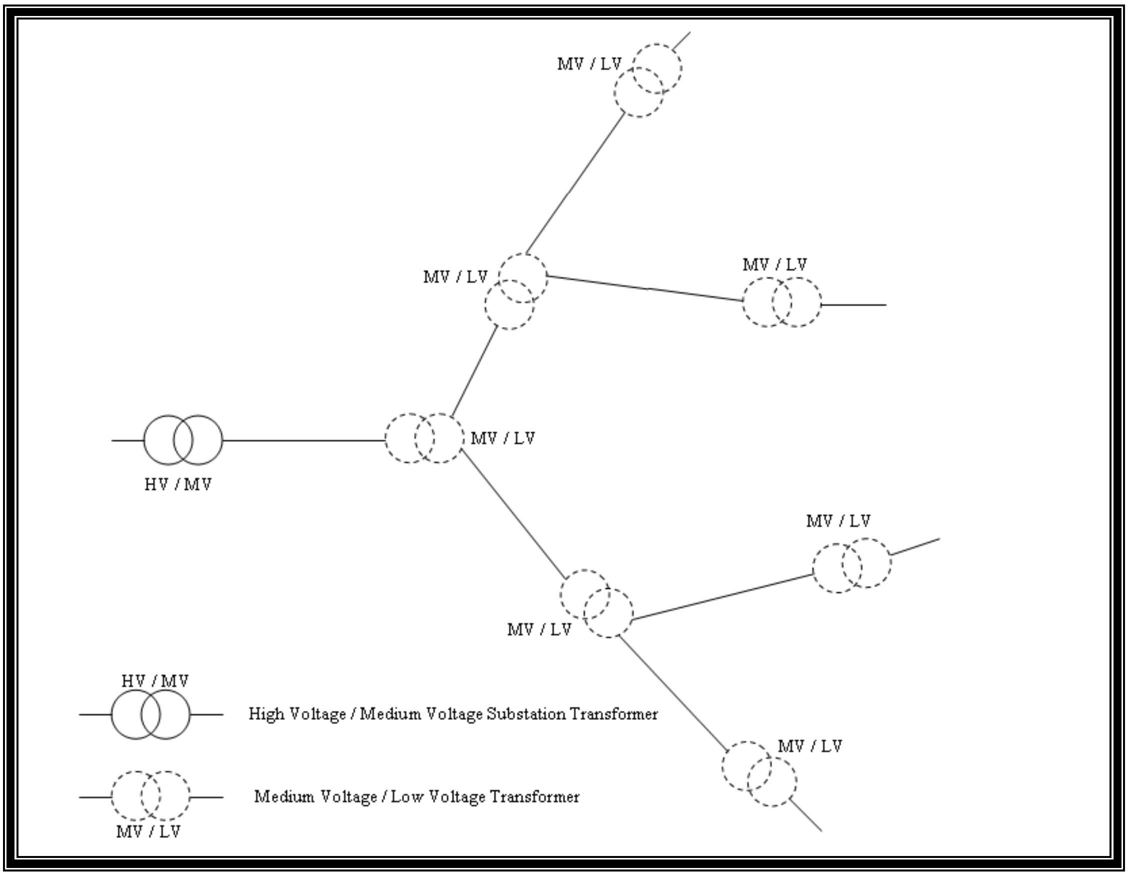

Figure 3.3: Radial Topology with Tree-shaped line

3.1.1.2 Ring Topologies

On the MV ring networks, the MV cable is running between the transformers, closing a loop via MV switchgears. Each switchgear is normally connected to three cables, cable one from previous transformer, cable two is connected towards the next transformer and cable three goes towards the local transformer. The ring shape enables power redundancy and come in use for PLC communication redundancy [Castro *et al* 05]. Ring topologies in Figure 3.4 appear to overcome a weakness of the radial topologies. The disadvantage of radial topologies is that the loss of one stretch of the MV line means interrupting the energy flow feeding the corresponding transformer substations. The ring topology cancel out the disadvantage of radial system and can be distinguished as an improved radial topology providing open tie points to other MV lines, therefore, creating a redundancy [Mohamad06].

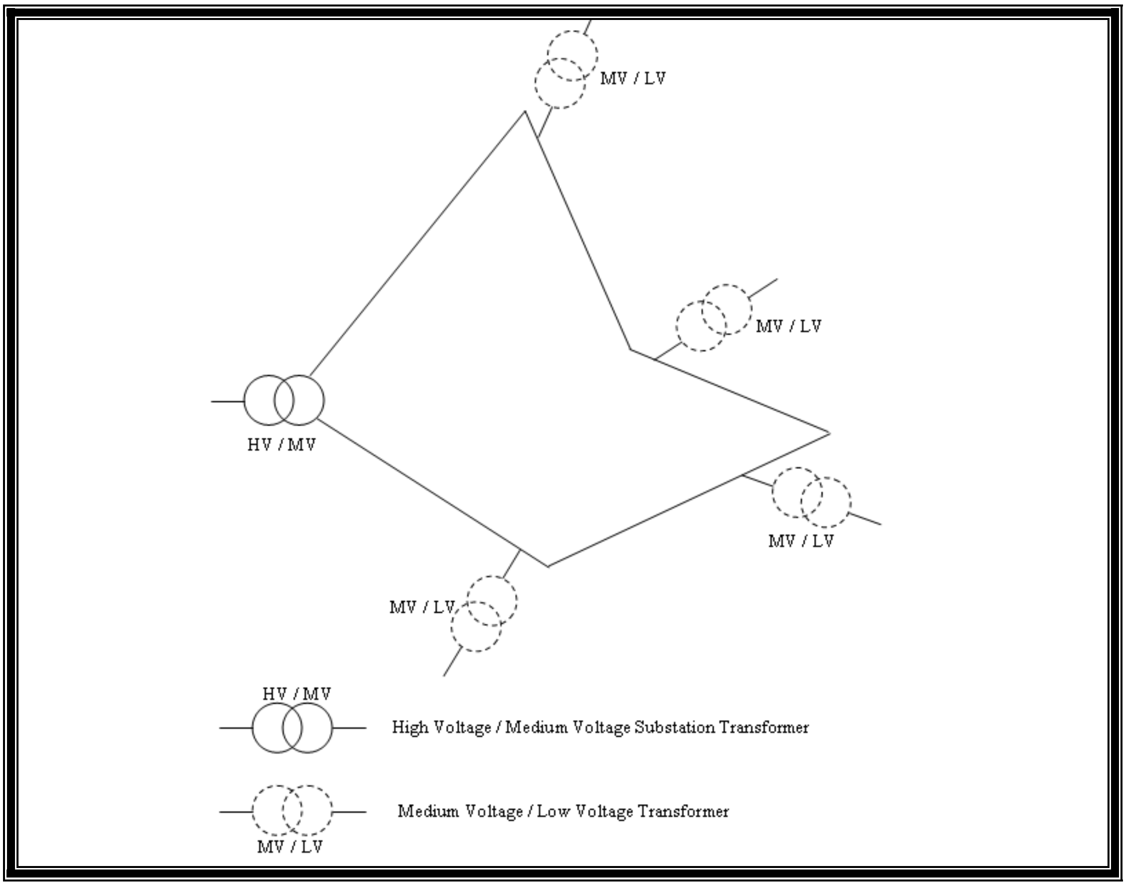

Figure 3.4: Ring Topology

These lines are still managed in a radial mode with one of the switchgears open in normal operation, but if a fault takes place on one of the stretches or lines, the tie switches allow some portion of the faulted line to be re-established quickly. Under normal cases, these switches are manually operated, but some power utilities use automated switches to perform these operations [Vazquez *et al* 05].

3.1.1.3 Networked Topologies

The MV networked or meshed networks in Figure 3.5 are similar to the MV ring network with a minor change in the number of connections per switchgear. Some of the switchgears on MV meshed networks consist of 4-6 connections, which enable switchgear to provide MV power to multiple remote transformers [Castro *et al* 05].

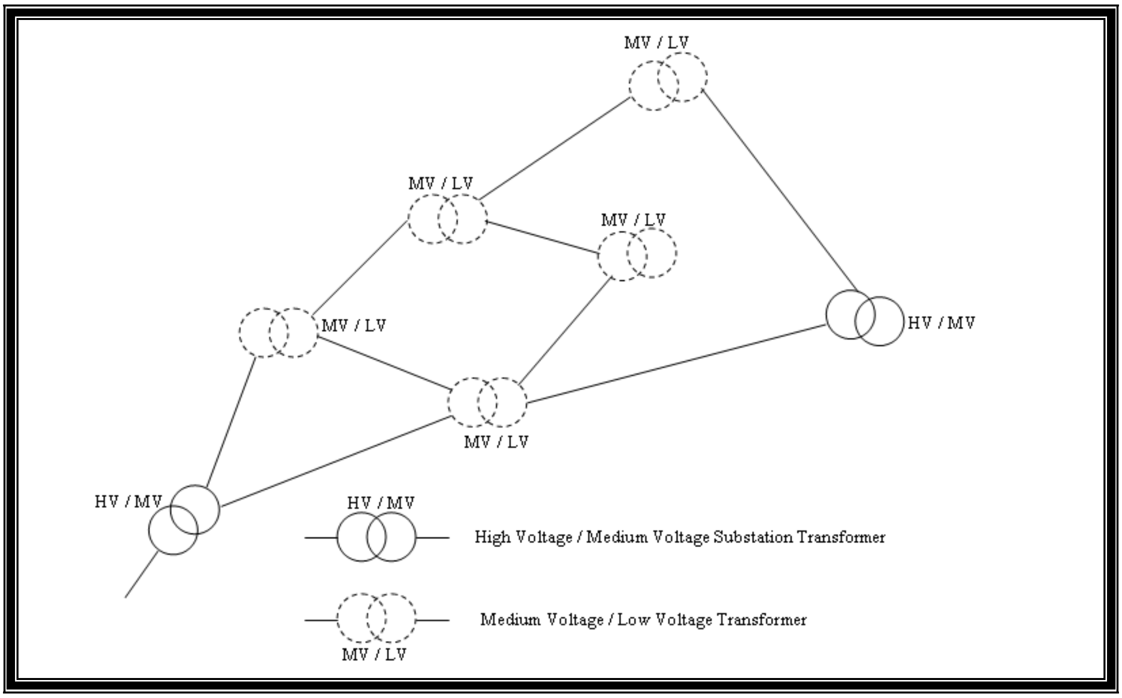

Figure 3.5: Networked Topology

In a networked topology, the electrical HV/LV substations and the MV/LV substation transformers are joined through many MV lines in a mesh as depicted in Figure 3.5. Several routes or multiple paths deliver the electrical power. If a line is removed from the service, power can be rerouted but these networks are more complex. The topology design requires calculating the network functioning in any possible condition and configuration [Mohamad06]. The MV networks or the primary distribution networks in general are networked but operating as radial topologies by opening certain stretches of the network. In the case of an MV line failure, others lines, which were disconnected, are connected to the network allowing to deliver the service again to all the transformers. In other words, the meshed network architecture accommodates unexpected growth and change more easily [Katsis *et al* 04].

3.1.2 Low Voltage Electricity Network Topologies

To distribute the power from the MV/LV transformer substation feeders to the connected customers, overhead or buried LV lines may be used. Although, from a voltage point of view, the LV area starts from the secondary of the MV/LV transformer and ends on the electrical plug socket of the customer [Zuberi03]. The following paragraphs, review the way the LV lines are arranged for the connection of the customer premises to the LV network. In the LV electrical network there are diverse possible topologies, but what type of LV electrical topology is utilized depends on the kind of the geographical area being served, the characteristics of the electrical loads, the country and of course the associated system of regulations defined by that particular country [Vazquez *et al* 05]. In principle the MV/LV transformer has numerous outgoing LV electrical feeders. However, there are also cases where transformers feeding only one line or more, sometimes the transformers feed only one but an important entity. In the general cases where several lines are fed by the same transformer several possibilities can be distinguished [Hrasnica *et al* 04].

A point to note, the terms used here are equivalent to the definitions and schemes in the previous section on MV electrical topologies. In the setting where the LV lines are feeding one unit, the topology is radial with exclusive lines as is the case with MV electrical topologies [Castro *et al* 05]. The LV electrical topology can also take the form of a classical radial topology with single line when the LV lines connecting electrical users are all connected at different points along the LV line [Vazquez *et al* 05] like in an Ethernet topology. When the LV feeder lines contain forks in their structure, comprising branches to the main line the topology becomes radial with tree-shaped lines more or less like the MV electrical radial topologies [Little02]. These structures enumerated here are very common and may coexist in the same LV network. The meshed structured LV grids are also common to different countries, these networks although meshed they supply electricity in a radial manner under normal conditions [Vazquez *et al* 05]. The loop structure is another possible form of an LV electrical topology, where the LV network comprising a line coming from a feeder, is looped back to another feeder. In standard conditions, the supplying mode may use open or closed loop configuration [Castro *et al* 05].

With this in mind, it can be said that in general, LV networks have mixed topologies rather than a pure one in all their lines. In all the cases presented above and whatever the structure may be LV topologies are composed of lengths clearly shorter than the MV networks. Even though, the variance in feeder lengths may be relatively large depending on the area being served, typically it can be concluded that some tenths of meters up to a few hundreds of meters are very usual lengths in the LV networks [Hrasnica *et al* 04]. It is important to note that lines of different phases can never be looped or interconnected. Power utility usually provides 3 sinusoidal power waves phased to each other. Each consumer device is connected to a single phase (active or neutral wires) or to a 3-phase (3 active or 3 active and neutral wires) system. But through the transformer coils and phase coupling high frequency wave from one phase is normally captured within another phase wire.

3.2 Preliminary Topology Designing Considerations - PLC Network Components

As mentioned in the preceding section, PLC networks use the electrical supply grids as a medium for the transmission of different kinds of information and the implementation of various communications and automation services through varied MV/LV topologies. However, the data communication signal has to be converted into a form that makes data transmission via the MV and LV electrical networks possible. Therefore, to fulfill such a purpose, PLC networks include specific data network elements that ensure proper signal conversion and signal transmission along the MV and LV electrical grids [Dostert01]. The main tasks of these basic elements being signal conditioning, signal conversion for its transmission and signal reception over the MV/LV networks. Following is the detailed review of the functionalities of the PLC devices that exist in every broadband PLC network. These PLC devices had a crucial in the investigation of this research as will be explained in the following sections.

3.2.1 Customer Premise Equipment (CPE) Modem

The customer premise equipment (CPE) or modem is the last element of the PLC network that connects standard communications equipment, used by the end-user, to the PLC transmission medium [Little02]. The CPE user-side provides various standard ports for different communications devices, such as ports for digital data transmission and analog telephony. On the other side, the modem is connected to the electrical grid using a specific coupling method (capacitive or inductive) that permits the feeding of communications signals to the electrical grid and reception of the communications signal from the electrical grid [Mitsubishi03]. The coupling guarantee a secure separation and act as a high pass filter by dividing the data communications signal (usually 10-30MHz) from the electrical power signal (50 or 60 Hz). The modem implements all the functions of the physical layer including modulation and coding. In order to reduce electromagnetic emissions from the electrical grid, the coupling is completed between two phases in the outdoor PLC and between a phase and the neutral conductor in the indoor PLC area [Dostert01].

3.2.2 PowerLine Communications Head End

Head End (HE) is the equipment connected on an existing standard backbone network such as Ethernet network and injects the PLC signal into the electrical grid. In other words, HE (base station or master station) connects the PLC system to the backbone network creating communication link and gateway between the backbone network and the PLC transmission medium [Hrasnica *et al* 04]. The HE may provide multiple network communications interfaces that can be used for the connection with the backbone networks using various communication technologies. Usually, the HE controls the operation of the PLC network. However, the network control or its particular functions can be distributed over the PLC network. In generality the HE can assume the functionalities of a PLC repeater or PLC gateway depending on the configurations governed by implementation factors in the environments in which it is installed.

3.2.2.1 PowerLine Communications Repeater

The distance between two nodes of the PLC network or between the HE and the slave is sometimes too big and the receiving equipment may not be able to get the data. In such cases, the use of a PLC repeater becomes necessary [Vazquez *et al* 05]. This so because of the high attenuation in the electrical grids, the use of repeaters (both in MV and LV networks) is sometimes mandatory to achieve the full coverage of the electrical network. This is expressed by the (BD*Delay) product value in communication networks where BD would be expressing transmission frequency and delay the physical distance of the segment. High frequency entails short distance of reach and vice versa. The PLC repeaters do not restrict the available resources and there is no logical limitation on their use in the PLC network. These devices have to be installed when really needed, in order to guarantee that the signal arriving to each receiving node can be handled appropriately [Lopez04], [Little02]. The repeater technique is not only necessary in the MV networks or between MV and LV networks but also within LV networks. In cases where the distances between PLC users placed in a LV supply network and between individual end users and the HE are too long [Hrasnica *et al* 04]. PLC repeaters divide a PLC network into several network segments. There are two types of repeaters, depending on the type of the network, network segments are divided using different frequency bands or by different time slots.

3.2.2.2 Time Division Transmission Mode Repeater

In the case of time division (TD) repeater Figure 3.6, a time slot (t1) is used for the transmission within the first network segment and another time slot (t2) is utilized for the second segment [Mitsubishi03]. To illustrate the TD repeater functionality, in this scheme if the communication between say A and B is done using the whole frequency band, then the communication between B and C will have to be done using the same frequency band, but during a different time slot or period in order to avoid collisions [Vazquez *et al* 05].

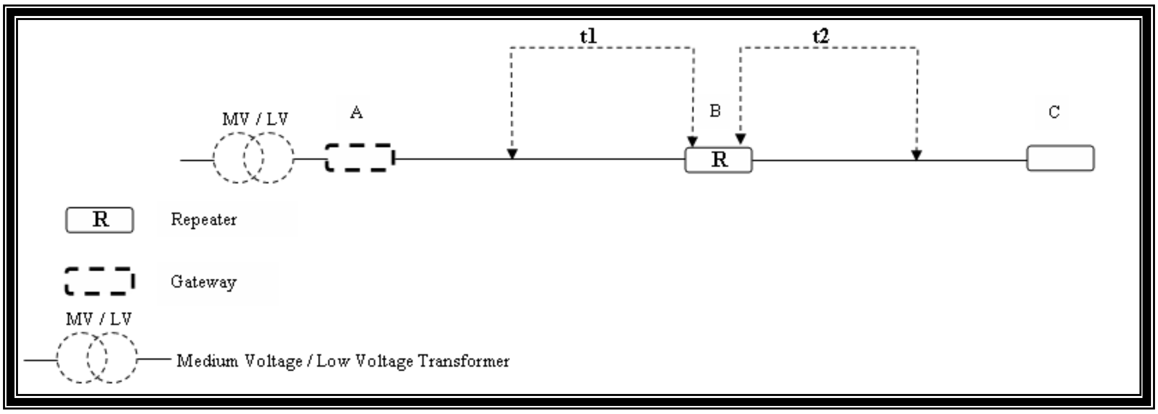

Figure 3.6: Time Division (TD) Repeater [Hrasnica *et al* 04]

The advantage of TD repeaters is that they are simpler, but typically provide higher end-to-end latency or delay, this is so because each re-transmission has to wait until the previous re-transmission has finished using the channel. Moreover, TD repeaters utilize the existing bandwidth less resourcefully, as very often the higher frequency bands are not very useful for long-distances, although they are used anyway in TD system [Vazquez *et al* 05].

3.2.2.3 Frequency Division Transmission Mode Repeater

The frequency-based transmission scheme in Figure 3.7 is based on system that, the repeater receives the transmission signal on one frequency band (f1), amplifies it and injects it into the network, but using another frequency band (f2).

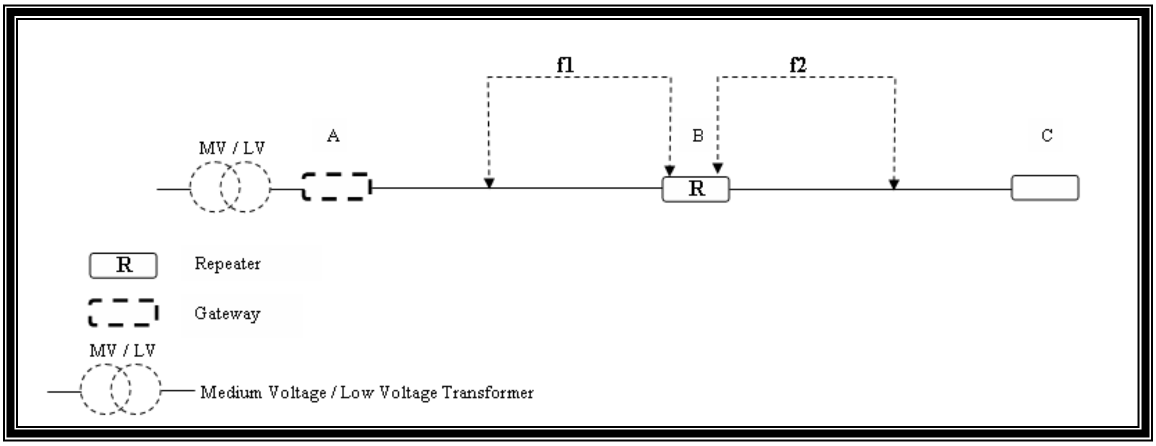

Figure 3.7: Frequency Division (FD) Repeater

In the opposite transmission direction, the conversion is carried out from frequency band f2 to frequency band f1 [Hrasnica *et al* 04]. To put how the frequency division (FD) repeater works differently, if for example the link between A and B only uses part of the frequency band, then the link between B and C can use a different band, while making use of the channel at the same time or simultaneously [Mitsubishi03]. Overall, it must be noted that a repeater does not modify the contents of the transmitted traffic, which is always transparently transmitted between the PLC network nodes. Theoretically, frequency range f1 could be used again within the third network segment. However, if there is interference between signals from the first segment, a third frequency range f3 has to be applied to the third network segment and frequency f4 to the fourth segment and so on. Consequently, with the growing number of different frequency bands, the common bandwidth is divided into smaller portions, which significantly diminish the network capacity [Hrasnica *et al* 04]. Though, the application of the repeaters does extend PLC network coverage, the application of repeaters also does increases the network costs through equipment costs and installation costs. Therefore, the number of repeaters within a PLC access network has to be kept as small as possible.

The FD repeaters are a bit more complex, in that they are normally built using two separate TD repeaters working at different frequencies, but they provide lower end-to-end latency. They also have the additional advantages of making a more efficient usage of frequencies that is lower frequencies may be reserved for long-distance, while higher frequencies are left for short-distance [Castro *et al* 05]. The decision on whether to implement TD or FD repeaters depends on the amount of nodes that constitute the PLC network. When the number of nodes is small it is better to opt for TD repeaters because this reduce the cost and ease the installation, but when the number of nodes increases the delay or latency increases and throughput decreases so it is justified to install FD repeaters. The FD approach is necessary in case of latency-sensitive services; the TD scheme cannot scale up, as does the FD scheme [Vazquez *et al* 05].

3.2.2.4 PowerLine Communications Gateway

On one hand, the PLC gateway is the technology that divides PLC outdoor network from the PLC indoor network. On the other hand, it also converts the transmitted signal between the frequencies that are specified for use in the outdoor and indoor settings. This type of a PLC gateway with such responsibilities is usually placed near the house meter unit. However, a PLC gateway can provide additional functions that ensure a division of the PLC outdoor and indoor networks on the logical network level [Hrasnica *et al* 04]. Therefore, the CPE connected inside the home network can communicate internally without information flow into the outdoor network. In this case, the PLC gateway will be controlling the indoor network by coordinating the communication between internal CPEs and between PLC indoor devices and the outdoor network. In general, the position of the PLC gateway can be anywhere in the PLC network providing both the repeater technique and network segmentation.

Using a gateway means, the PLC network can be divided into several sub-networks that use the same physical transmission medium in the same network. Additionally, the gateways control these sub-networks and internal communication within the sub-network is carried out by the responsible gateway. In other words, the communication between a CPE of a subnetwork and the HE is possible only over a responsible gateway. The network can be organized in such manner that the HE has direct control over a number of subnetworks [Vazquez *et al* 05]. PLC gateways are connected to the network in the same way as the PLC repeaters. As is the case with the PLC repeater, an increasing number of PLC gateways within a PLC network increases the network latency and causes higher costs. Nonetheless, where the PLC repeaters provide only simple signal forwarding between the network segments, the PLC gateways provide intelligent division of the available network resources, thus, guaranteeing better network efficiency.

3.3 Broadband PLC Topologies

3.3.1 Broadband PLC Medium Voltage Network Topologies

The MV network is the collection of MV/LV substation transformers, which are interconnected to each other through MV lines of their respective transformers. All the data traffic from each MV network is concentrated on either the MV/LV substation or the HV/MV substation, which in turn is hooked up to the backbone network [Vazquez *et al* 05]. This section tackle the building of reasonable MV PLC topology models for the connection of multiple PLC MV networks, confined within a smaller geographical area; this is achieved by designing MV PLC topologies that attach a number of these MV PLC networks. The designing of these MV PLC networks in this research is accomplished through designing different PLC topologies independent of the applied communications backbone network technology. The MV PLC topologies presented in the following subsections were designed with the goal to ensure cost-effective and reliable PLC medium topologies that include redundancy in the case of failure and this in the real world depends primarily on the location of the PLC medium networks in a chosen area and on the proximity of these MV PLC networks to the backhaul/backbone network. The backbone network is defined in this research as the set of equipments and infrastructures that establish the communication between MV PLC network and the Internet Service Provider (ISP).

3.3.1.1 Proposed Medium PLC Bus Network Topology

In the MV network, the bus topology is one of the possible MV PLC topology that can be designed at low costs. The bus model in Figure 3.8 is proposed for a setting where a single or dual MV cable runs along the MV/LV transformers. Each MV/LV transformer receives a cable that is notched from the main cable. The MV/LV transformer has a single point of connection to the MV main cable in each individual node [Garrigosa05]. The HE is placed in the HV/MV substation where it is connected to the backbone network (between ISP and the MV PLC network). The other HEs are installed in the MV/LV substations [Vazquez *et al* 05]. The distance between the HV/MV and the MV/LV substation vary between 100 m to 1 km as shown in Figure 3.8. PLC cannot adequately transmit over a distance of 1 km so repeaters will be positioned in between at a distance not exceeding 100m. The distances between the MV/LV substations on the MV cable vary between 150 m to 400m [Escalona *et al* 05] and repeaters can be positioned at a spacing of not more than 100m.

The HE in every location should be able to interconnect to the MV network and deal with PLC communication signal from MV network. In addition, every PLC unit in the bus model can receive every other PLC unit on the network [Castro *et al* 05]. The PLC data traffic is conveyed from the HV/MV gateway to the MV/LV gateways bidirectionally. However, the cost factor is not the only single criterion for the decision about PLC topology design on the MV network.

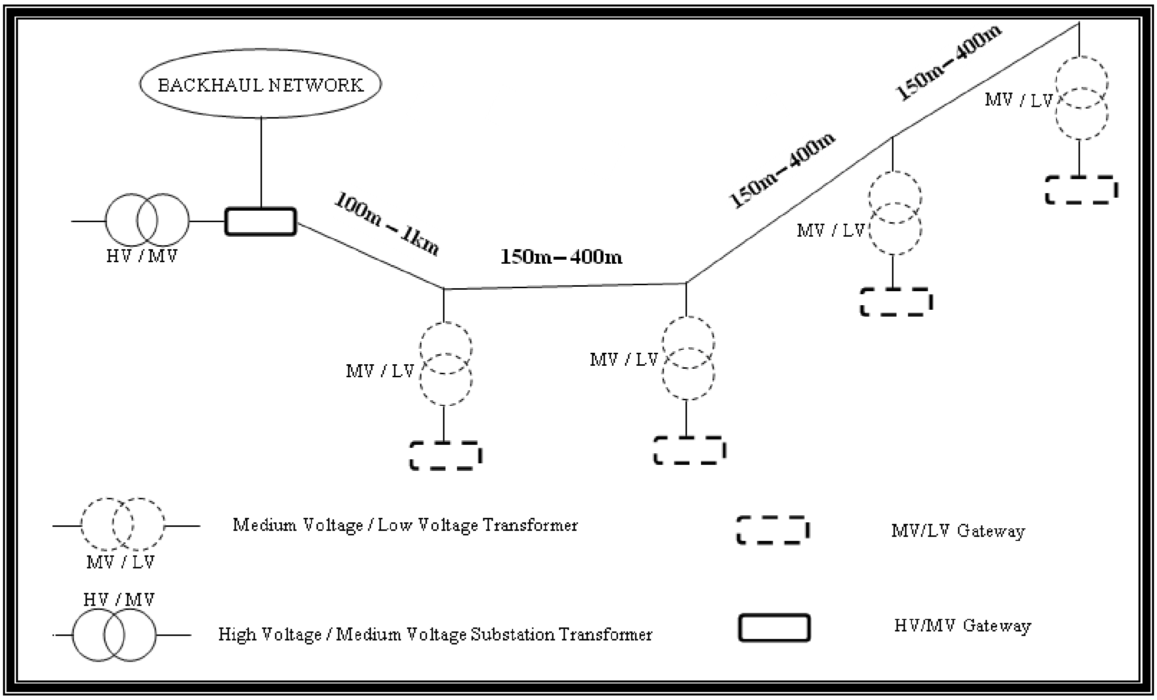

Figure 3.8: Proposed Medium PLC Bus Network Topology

An important criterion to be considered is network reliability in the case of link failures. The proposed bus model in Figure 3.8 has the constraint that if a link between two MV HEs breaks down, all MV network nodes placed behind the failed connection gets disconnected from the backbone network [Tanenbaum03]. In other words, a break in the MV segment causes the entire PLC MV network to be inoperable until the break is repaired. So for availability of the communication services it is important to evaluate the level of redundancy and the (MTR) offered by the utility.

3.3.1.2 Proposed Medium PLC Star Network Topology

As presented in Figure 3.9, the proposed star design connects each MV/LV network node independently to the HV/MV gateway. The adequacy of the star model as a PLC topology is that it matches well with application of DSL technology as a backbone network in the PLC networks [Escalona *et al* 05]. In a star topology, all MV/LV HEs are attached directly to the central HV/MV gateway that establishes and maintains connection between them.

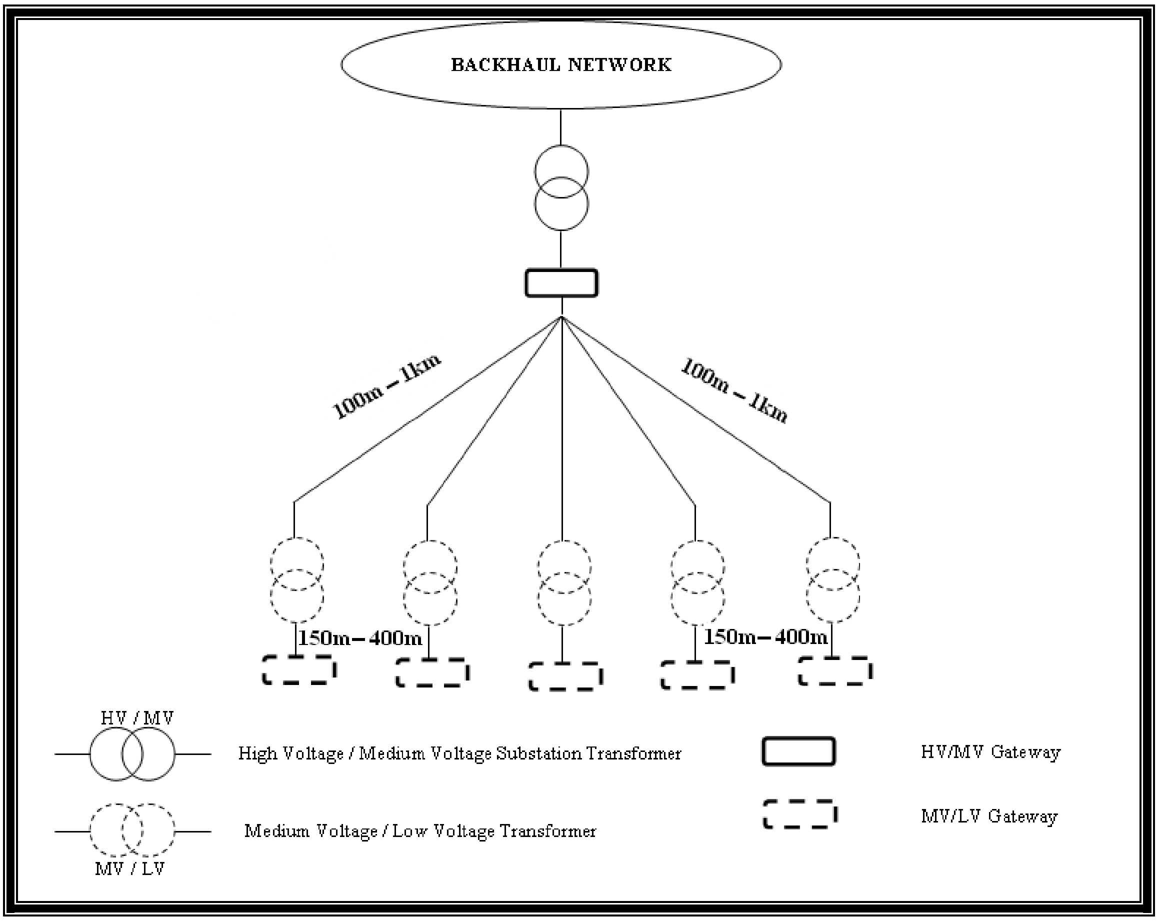

Figure 3.9: Proposed Medium PLC Star Network Topology

The distance between the HV/MV substation and MV/LV substation is from 100 m to 1 km as is depicted in Figure 3.9. On the other hand, the distance between one MV/LV substation to with another MV/LV substation varies from 150m to 400m 3 or 4 repeaters will be installed in between a distance of 400m. In each MV/LV transformer, a single PLC unit should be able to interconnect to the MV network via two or more capacitive or inductive coupler in order to deal with PLC communication on multiple ends of the MV network [Castro *et al* 05]. A failure of a single link in the star network disconnects only the MV/LV HE attached to it. This is advantageous in that it isolates a failed link but there is no possibility for an alternative connection of the affected MV/LV path to the backbone over a redundant link [Chen05], [Marie *et al* 05]. In other words, there are no multiple paths to reach each MV/LV node.

The advantage of this topology is that it is easy to isolate the problem but if the HV/MV HE malfunctions or fails the entire PLC system is compromised. The star model fails miserably if the HV/MV gateway goes down, this is so because much is centralized around the HV/MV gateway. The HV/MV gateway is not only a single point of failure but also it is a potential bottleneck in that it will likely become congested as more MV/LV HE nodes are added [Castro *et al* 05],[Tanenbaum03]. The problem is prevalent when it is a master slave setting but when the MV/LV HE nodes are in a peer to peer scenario the problem of a single point of failure is solved. This so because the MV/LV HE nodes are not only slaves now but acting also as masters this is possible because all are physically connected to the same phase lines. It must be noted that collision avoidance (CSMA/CA) can be replaced by priority based Round Robin MAC like in high speed LAN IEEE 802.12.

3.3.1.3 Proposed Medium PLC Ring Network Topology

In a ring model Figure 3.10, the MV transformer has a two points of connection to the MV main cables forming a circle [Noguchi04]. In each individual transformer, a single PLC unit in every location should be able to interconnect to the MV network via capacitive or inductive coupler in order to deal with PLC communication on both ends of the MV network [Castro *et al* 05]. All the PLC MV/LV nodes and the HV/MV gateway node are designed in such a way that they are connected to one another in a closed loop configuration [Garrigosa05]. In this topology, every node only connects to the next neighborhood node. The last MV/LV node connects back to the first HV/MV node [Chen05], [Lopez04].The HV/MV substation and MV/LV substations are separated by a variable distance of 100 m to 1 km as shown in Figure 3.10.

The proposed ring topology seems to be a reasonable topology solution for increasing the network reliability given the drawbacks of the star model enumerated in the previous section. In the case of a link failure between the MV/LV PLC nodes, there is always an opportunity for alternative transmission links. The MV/LV substations have approximately 150m to 400m between them and for a distance of 400m repeaters can be spaced at less than 100m.

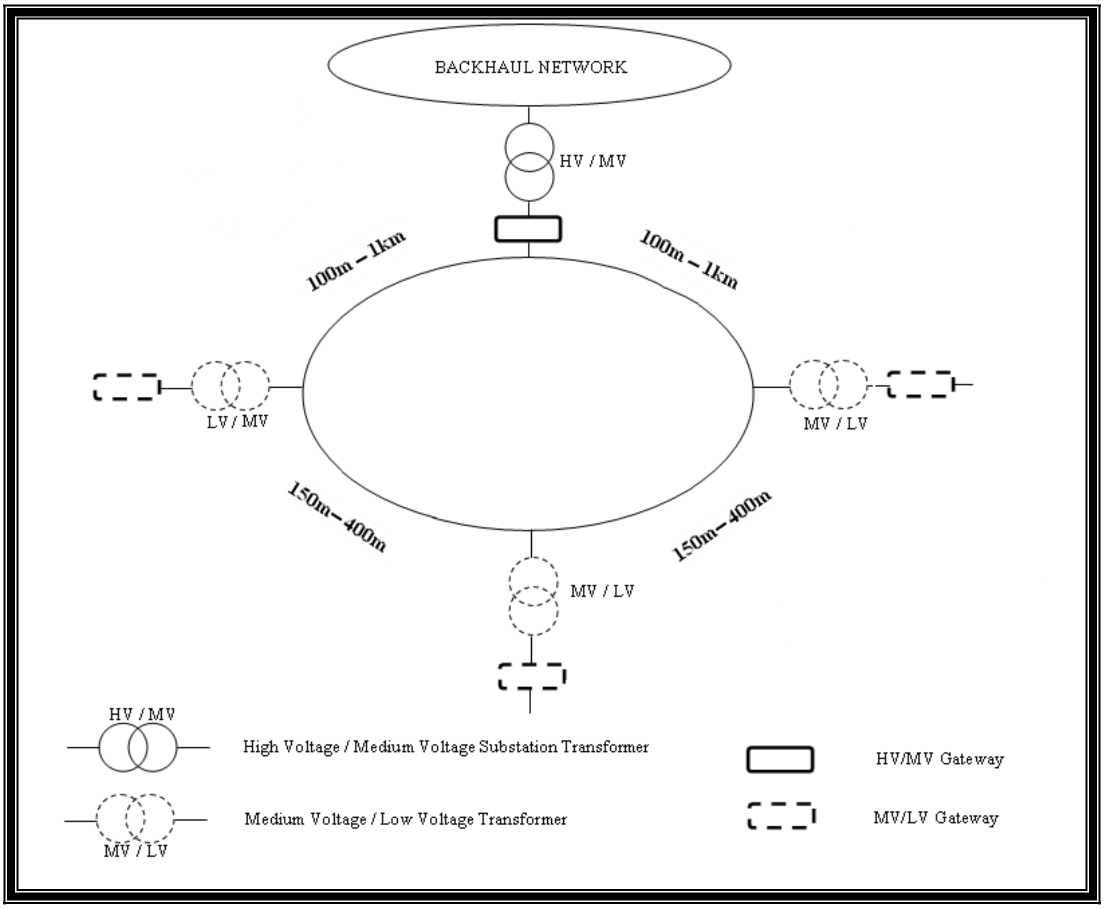

Figure 3.10: Proposed Medium PLC Ring Network Topology

The model has the local intelligence to send the services affected via an alternate path without a lengthy interruption in case of a link failure [Katsis *et al* 04]. Of course, reorganization of the transmission paths between the MV/LV PLC nodes and the backbone network through the HV/MV gateway has to be done automatically within a short period of time. The demand for survivable services, diverse routing of facilities, flexibility to rearrange services to alternate serving node makes a ring an advantageous topology [Arriola05]. The topology of a PLC distribution network can also be a combination of any of the three basic network structures presented above. Though, network centralization is at minimum, the model reaches failure quickly because of weak redundancy [Castro *et al* 05].

3.3.1.4 Proposed Medium PLC Partial Ring Network Topology

The full ring design can sustain single failure, but when there are two simultaneous failures, network segments became unreachable because of the lack of redundancy [Katsis *et al* 04] making PLC unable to maintain a contiguous network [Escalona *et al* 05].

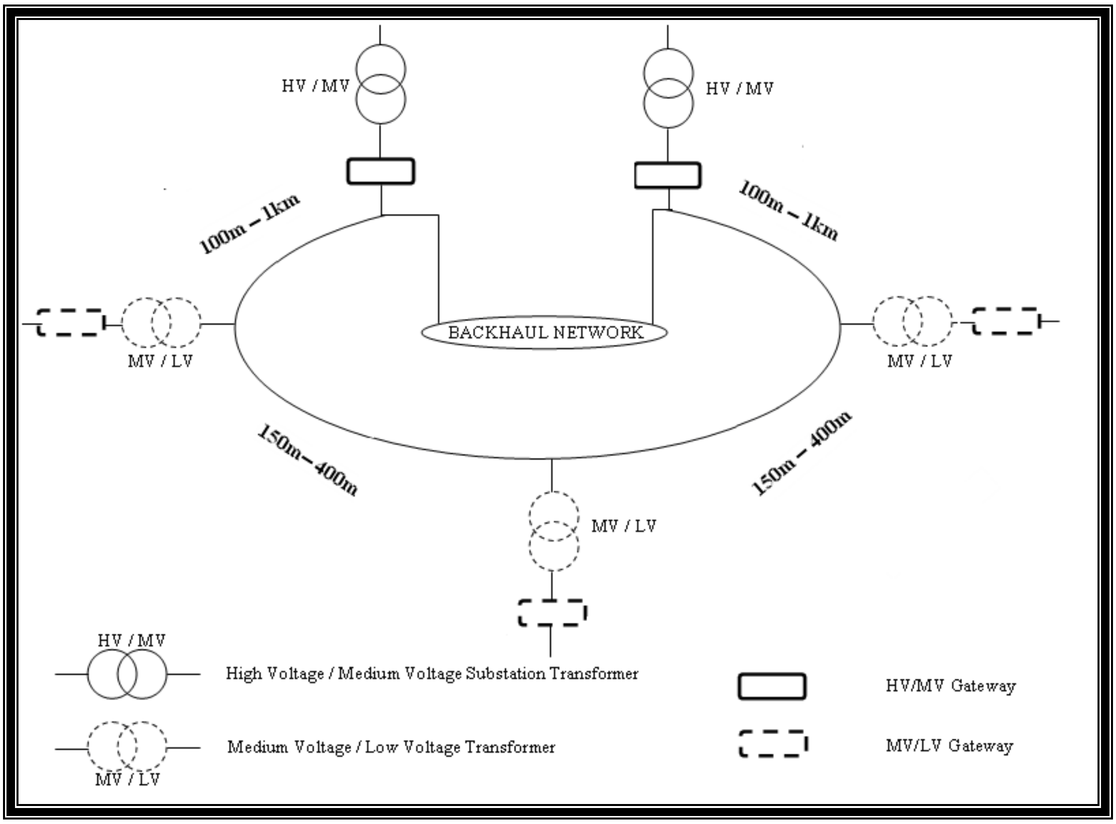

Figure 3.11: Proposed Medium PLC Partial Ring Network Topology

So another variant of the ring topology, partial ring topology design Figure 3.11 is proposed in such a case. Unlike the full ring design, the partial ring has 2 HV/MV gateways both individually connected to the backbone network designed to overcome the issue of having one single point of failure (single HV/MV gateway). The distance between the HV/MV substation and the MV/LV substation is from 100 m to 1km. While the distance between adjacent MV/LV substations vary from 150m to 400m. So repeaters will be placed at a distance of not less than 100m for PLC nodes to sufficiently transmit data signals. The partial ring model is proposed to overcome the vulnerability of simultaneous link and gateway failures. The second HV/MV gateway is included to leverage the traffic load and add redundancy in the network in case of concurrent failures, thus improving on the full ring structure and eliminating some of the drawbacks of the full ring topology [Escalona *et al* 05].

3.3.2 Broadband PLC Low Voltage Network Topologies

Three main factors influencing the LV PLC architecture are:

- Firstly is the network location. The PLC network can be located in a residential or business area and additionally there are differences between these settings as it is between rural and urban residential localities. It is usually the case that business areas are distinguished by high numbers of potential users of PLC services [Vazquez *et al* 05]. It is also expected that subscribers from the business areas have different requirements than the subscribers from the residential areas. This disparity in requirements is similar to the differences in requirements that exist also between urban and rural areas.

- Secondly, the factor that has an effect on the LV topology architecture is the user density or the population of the PLC users in a given zone [Beamud *et al* 03]. The number of users in a LV network as well as user concentration varies from zone to zone. The user can be mostly located in single houses, the rural areas best typify this situation, or within small blocks including several individual users as in urban residential area (low user density) and in buildings with a larger number of flats, offices, within apartment, business or commercial quarters (high user density) [Hrasnica *et al* 04].

- Thirdly, network length has influence on the design of the LV PLC topology. The distance between the transformer substation and a PLC user within the LV network differs from place to place [Hrasnica *et al* 04]. More often than not, there is a considerable network length difference between the urban and rural settings. Finally, network design is a factor that affects the LV topology architecture. The LV networks are usually comprised of several network branches of varying number, which differ from one LV network to another and this affects the LV PLC architecture in a great way as will explained and depicted in the following sections [Vazquez *et al* 05].

For the purposes of the figure annotations presented in the following sections, fuse boxes are an example of street cabinets, they are installed at the head of each connection to the LV distribution network as protection and switching devices [Vazquez *et al* 05]. Their function is to protect the public distribution network against any important short-circuiting they may be placed outside or inside the building but either way, they have to be always accessible. Meter rooms group or centralize meters, protection devices and mains distribution devices into one location usually in the basement or the ground floor [Marie *et al* 05]. The mains distribution box is the alternative solution for buildings not using a meter room. The main is distributed to each floor where it feeds the flats through individual branches [Hrasnica *et al* 04]. The meter location can vary between several possible cases it can be outside the house on the same panel with the fuse-box, inside the house on the same panel with the general circuit-breaker, near the entrance alone or it can be inside near the distribution board.

3.3.2.1 Proposed Local PLC Topology Architecture First Model

The architecture of the first model relates to low density residential areas, comprised primarily of single houses and small buildings of apartments. This kind of a topology is suited for low density residential deployment as explained earlier in this section and the proposed topology design model is depicted in Figure 3.12. This LV model fits where the fuse boxes feed up to 4 households with individual electrical meters. The topology was designed with the HE installed in the MV/LV transformer station. In order to get good performance, the distance between the repeaters or the distance between the gateway and a repeater should not be more than 100 m [Marie *et al* 05], [Noguchi04]. Generally, it means that there are 3 to 4 PLC repeaters in a feeder line of 300 m long.

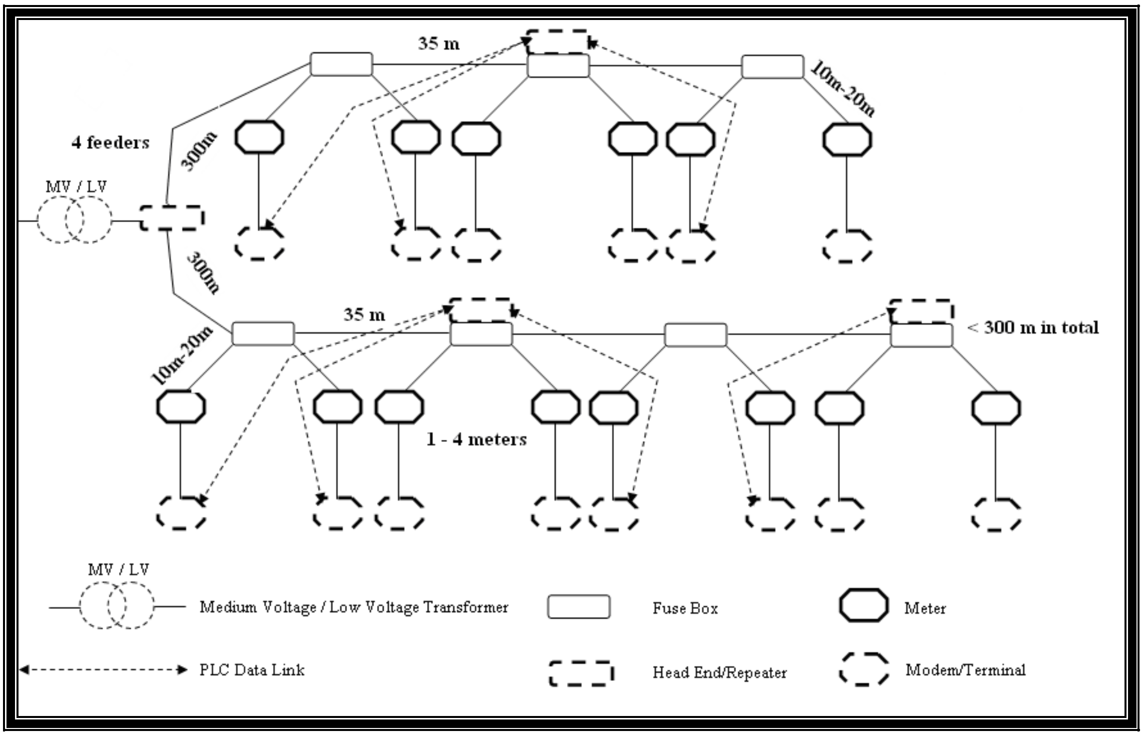

Figure 3.12: Proposed Local PLC Topology Architecture First Model

Another requirement that needs consideration is the distance between the PLC repeaters and the CPE [Vazquez *et al* 05] which can vary from 10 m to 20 m as shown in Figure 3.12 below. In instances where the distance in between is long, it will be necessary to install extra intermediate repeaters to increase the performance of some of the CPEs.

3.3.2.2 Proposed Local PLC Topology Architecture Second Model

The second model topology designed in Figure 3.13 corresponds to residential areas of high-density comprising several households where electrical meters are collected in a meter room. There are direct feeder lines of connection from the transformer towards the meter room, with a distance of 200m which may serve up to more or less 30 households [Pavlidou *et al* 04]. The model considered here is the star topology, which is created, in this setting, when the electrical feeder line from the MV/LV transformer goes directly to the meter room. The distance between the MV/LV and the meter room is approximately 200 m, so 2 repeaters at distance of not more than 100m will be positioned in between.

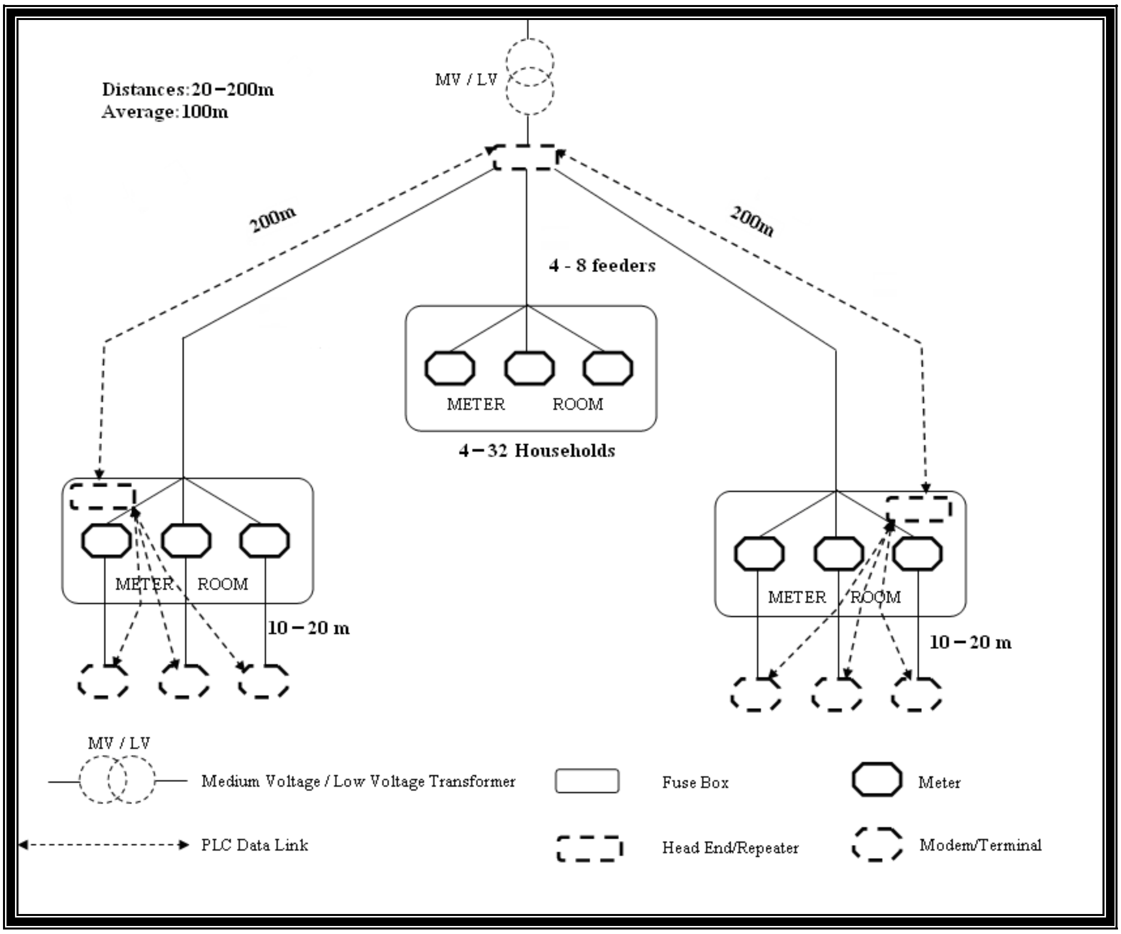

Figure 3.13: Proposed Local PLC Topology Architecture Second Model

With this model, the installation of the PLC HE is done in the MV/LV transformer station. In Figure 3.13, a proposed PLC star topology is presented. In each transformer a single PLC should be able to interconnect to the MV network via two or more capacitive or inductive coupler in order to deal with PLC communication on multiple ends of the MV network [Marie *et al* 05]. This is the easiest topology design because the PLC gateway is installed in the transformer station and the PLC repeater in each meter room [Lopez04] with a spacing less than or equal to 100m between them. In this topology the feeder line is 200m and if 3 repeaters are placed, the spacing between will approximate to 70 m. The distance between the HE in the meter and the CPE vary from 10m to 20m as depicted in Figure 3.13. The proposed second model shares the medium from the HE to a set of slaves. Therefore, a repeater will be a slave in the first link and at the same time be a master of the next repetition section, as it is done similarly by the IEEE 802.12 MAC protocol.

3.3.2.3 Proposed Local PLC Topology Architecture Third Model

As is with the previous star design in Figure 3.13, this third model appears also in areas of high density with buildings of several households. In Figure 3.14 just like the star topology, the meters are concentrated in meter rooms [Gomez05]. However, unlike the previous star design in this setting there is more than one meter room connected to each feeder line of 250 m forming a tree topology design as illustrated in Figure 3.14. In this model, repeaters are set up or placed in the meter rooms with at a spacing of not more than 100m. For 3 repeaters in a feeder line of 250m the spacing will approximately be 90 m and but for 4 repeaters the distance reduces to 60 m. In those cases where the distance between the MV/LV transformer gateway and the meter room is huge, additional PLC repeaters are then installed in the intermediate fuse boxes at 100m points. The fuse boxes have a distance between them of 40m to 50m [Vazquez *et al* 05].

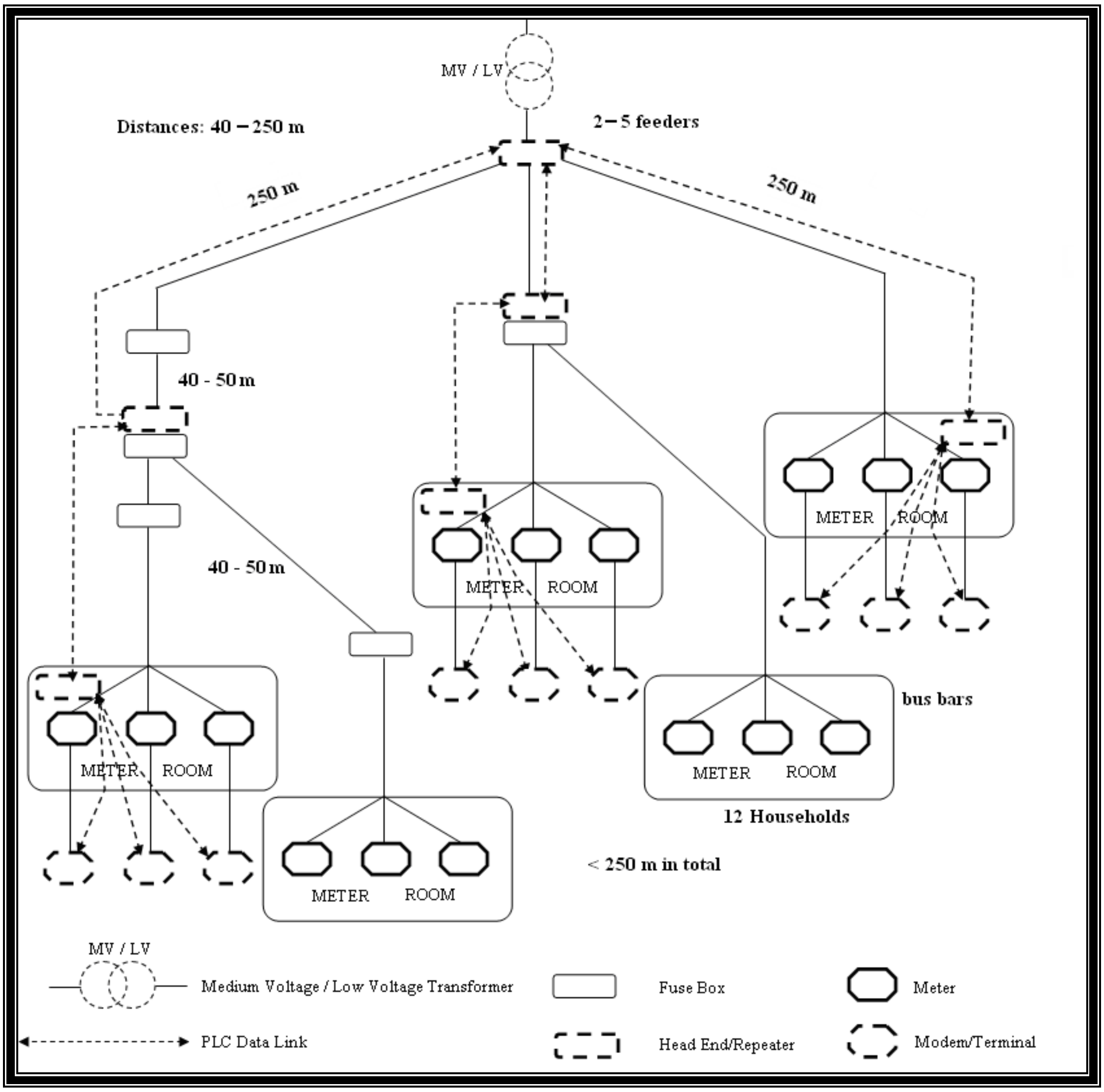

Figure 3.14: Proposed Local PLC Topology Architecture Third Model

3.3.2.4 Proposed Local PLC Topology Architecture Fourth Model

The fourth model presented in this section corresponds again to high-density areas with high-rise buildings where the distinct attribute is that electrical meters are distributed in different floors [Escalona *et al* 05].

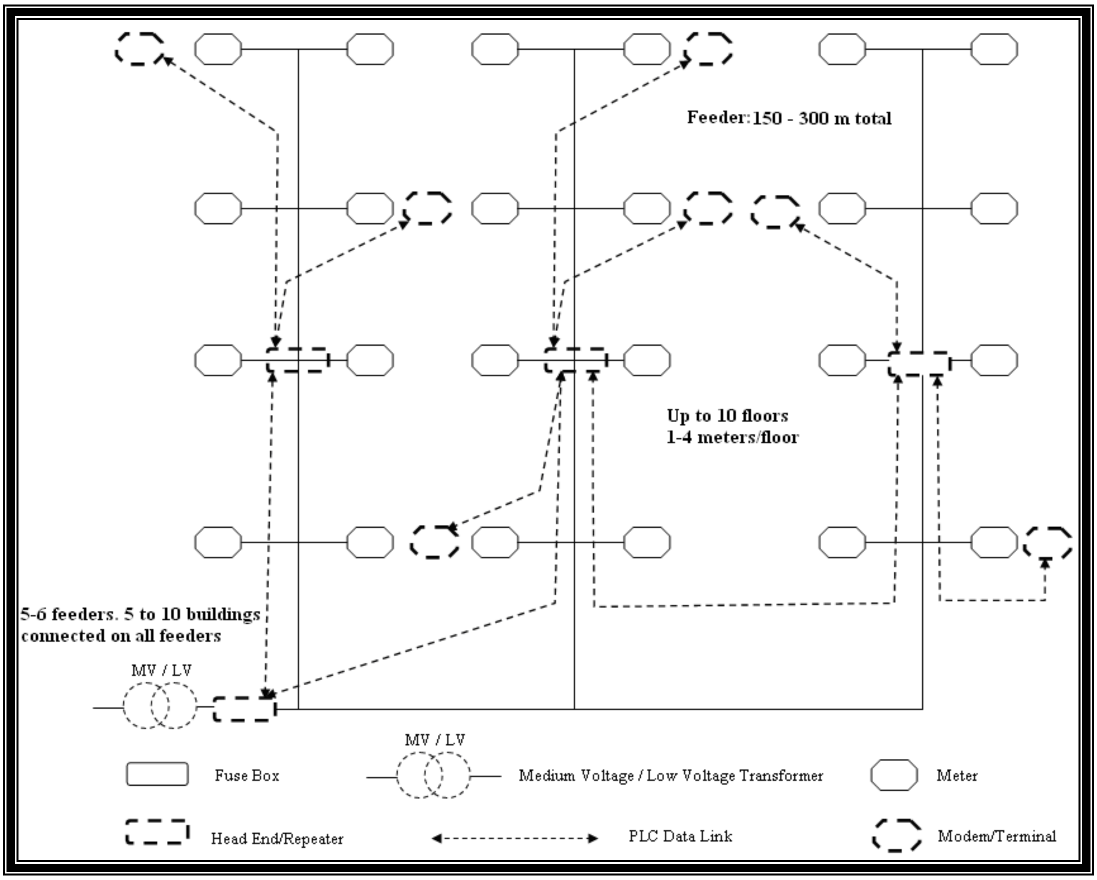

Figure 3.15: Proposed Local PLC Topology Architecture Fourth Model

This topology is quite similar to the star topology designed in Figure 3.14 but the difference is that in this design the electrical meters are spread in different floors. The PLC HE normally is installed in the MV/LV transformer and PLC repeater is installed inside each building creating a star design as shown in Figure 3.15. The distance between the MV/LV HE and the repeater should not be more than 100m. The length of the feeder lines varies from 150 to 300m [Anatory04] so, for 3 repeaters the spacing will be 100m. If the signal the distance is still huge the number of repeater can become 4 with a spacing of 80 m in between them. The PLC repeater should be as centered in the building as possible in order to cover the whole building [Vazquez *et al* 05]. The distance between the PLC repeater and the PLC modem can vary from 10 to 20 m. For example in a storey building comprising six floors the PLC repeater should be at floor three, but it can be placed in the second floor to increase the throughput with the MV/LV PLC gateway.

3.3.3 End User Requirement Based Local PLC Topologies

The task of planning a network commence by embarking on a thorough study of user application requirements in order to come up with a topology that best serve some well-defined purposes [Dooley01]. The following PLC topologies were designed, by analyzing user requirements in different possible user settings before providing technical topology solution. From the analysis of the requirements of these different possible user settings and physical topology constraints, logical topologies were extracted and utilized in proposing different topology designs. This approach allowed the technical analysis to be reduced to those PLC topologies which actually cover user requirements. In this research there are mainly two types of users, namely, home users and office or professional users. The demands of these different kinds of users are different as it is in the real PLC networks where both professional and home users are found.

As described previously in this chapter, the PLC equipments that take part in the designing of LV topologies are the head end (HE), repeaters and customer premise equipments (CPE). A brief revisit of what was defined before, HE is the point of access to the backbone network [Garcia *et al* 03]. Repeaters are implemented based on need that is to say, depending on the link capabilities between the HE and the CPE. Lastly, CPE is the device to which the customer network is attached [Lopez04]. The most important issue regarding PLC logical topology design is related to the router or bridge functionalities. In all the following set-ups, the HE will act as a router or repeater. The CPE may assume the responsibilities of a router or bridge depending on the situation. Repeaters are only used when there are long distances or the number of users is high [Pavlidou *et al* 04] and this research assumes that the repeaters are always present in the topologies. The goal is to achieve a good trade-off to satisfy the user requirements and at the same time reduce cost of the equipments and the operation costs. Therefore, the following sections will analyze and propose different topology possibilities to get the better role for each of the PLC devices.

3.3.3.1 Proposed Local PLC Model for Home End Users Requirements

3.3.3.1.1 Home End Users Requirements

The home end users topology is proposed for broadband residential local networks, where the connection of multiple devices is within homes. The simplest broadband home networks are used to connect two or more computers for sharing files and printers to access basic services like e-mailing and web browsing. This research acknowledge a PLC home network as mainly a network segment which has possibly no dedicated server and where very high levels of performance and robustness are not warranted [Garcia *et al* 03], [Tanenbaum03]. The home users setting is typified by users who wish to use the PLC connection at home during leisure time and usually they do not have different terminals and do not provide services. They do not mange their own web or mail servers, their own DNS. Most of the services they access are provided outside the PLC network. However, future PLC trends indicate that each time more home users are having several devices require the possibility to provide services such as access to home networking device from the outside home. Some of the requirements for these home users are:

- Connectivity to Internet for elastic applications such as electronic-mailing
- Web-browsing and file downloading for example games, music.
- Audio and Video streaming with minimal quality of service requirements.
- Real-time IP-based services like telephony, videoconferencing, which usually requires some quality of service, guarantees.
- A network with not many workstations typically one PC (or one printer/scanner) and a few automation devices [Beamud *et al* 03].

3.3.3.1.2 Home End Users Networking

Most of the configurations in the user requirements and networks are automatic so that the network operator does not require big expenses in customer support [Pavlidou *et al* 04], [Dooley01]. This certainly reduces the costs and simplifies the deployment, configuration and operation of the PLC network. These users will use one or several computers with an internal network. For all these functionalities, they rely on the network operator. The proposed topology solution for the home users is shown in Figure 3.16.

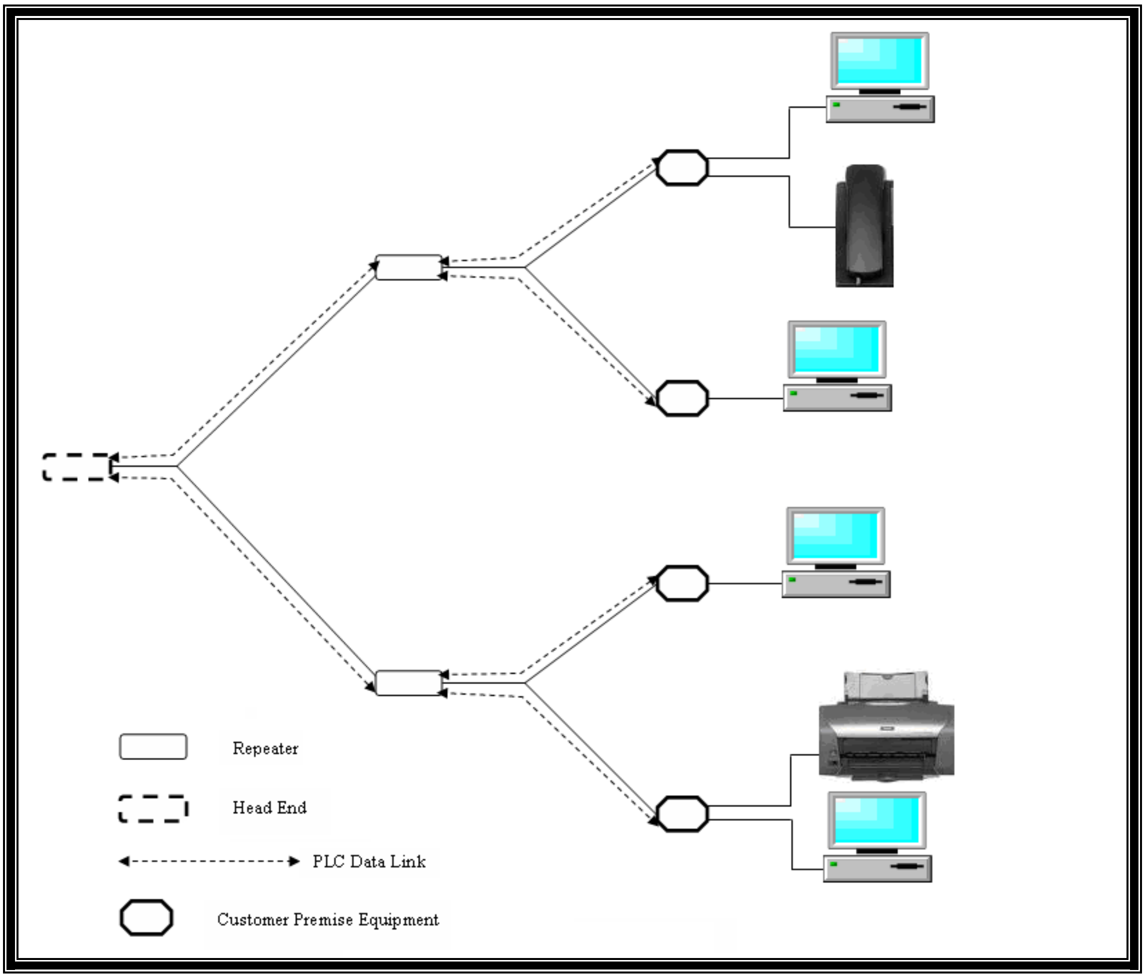

Figure 3.16: Proposed PLC Topology Model for Home End Users

The possible ways considered in designing this topology were, the CPE becomes either a bridgeable CPE or routable CPE. For the home equipments to get auto configured the best approach in this setting is that CPE acts as a router. Thus, the HE will announce addresses to the CPE, which will in turn advertise these addresses into its PLC customer network. This will easily allow and support the automatic additions of more devices by the customer without need to alter anything in the configuration of the PLC network [Beamud *et al* 03].

3.3.3.2 Proposed Local PLC Model for Office End Users

3.3.3.2.1 Office End Users Requirements

In the office end users environment, the users need higher computing service, higher bandwidth, complex network services, and security mechanisms to best serve productivity. It does not matter whether the area is urban or rural, professional customers need secure connection for intranet and applications, symmetric uplink/downlink capacity for file exchange and sufficient bandwidth to support the implementation of innovative services like fast Internet, VoIP and videoconference [Pavlidou *et al* 04], [Tanenbaum03]. The requirements of office users may include among others the following:

- The internal network comprises multiple terminals connected, whose number depends on the size of the company.
- The network may span over different parts of the building that introduces the issue of different workgroups and trunk traffic load.
- Network applications are still required as in home user setting for example web browsing, e-mailing supported by common servers.
- Bigger aggregate bandwidth for both real-time and elastic applications and the characteristics traffic over the network segments is varied across the board.
- Large databases, mainframe applications and related client/server applications for transaction processing [Dooley01].
- High level of security and access right to shared resources.

3.3.3.2.1 Office End Users Networking

The office user requirements raised above provide a good point of departure, which enabled the following detailed and comprehensive topology design depicted in Figure 3.17. The users for this kind of topology would be entire networks and who may even have their own routers, firewalls and servers. Given the set of these requirements and provided that a CPE that acts as a router would cause the networking tasks such as address delegation to become extremely complex [Beamud *et al* 03] and cumbersome this research advocated for the use of a CPE acting as a bridge instead. The networking functions mechanisms are performed from the HE to the router owned by the office user. The router is installed in the user premises and is under the control of the office end user. PLC HEs were incorporated in the design in Figure 3.17 because routing scales much better than bridging when large numbers of devices need to communicate with one another, as is the case in a real office set-up where the network is dynamic in almost every aspect from time to time [Tanenbaum03], [Vazquez *et al* 05].

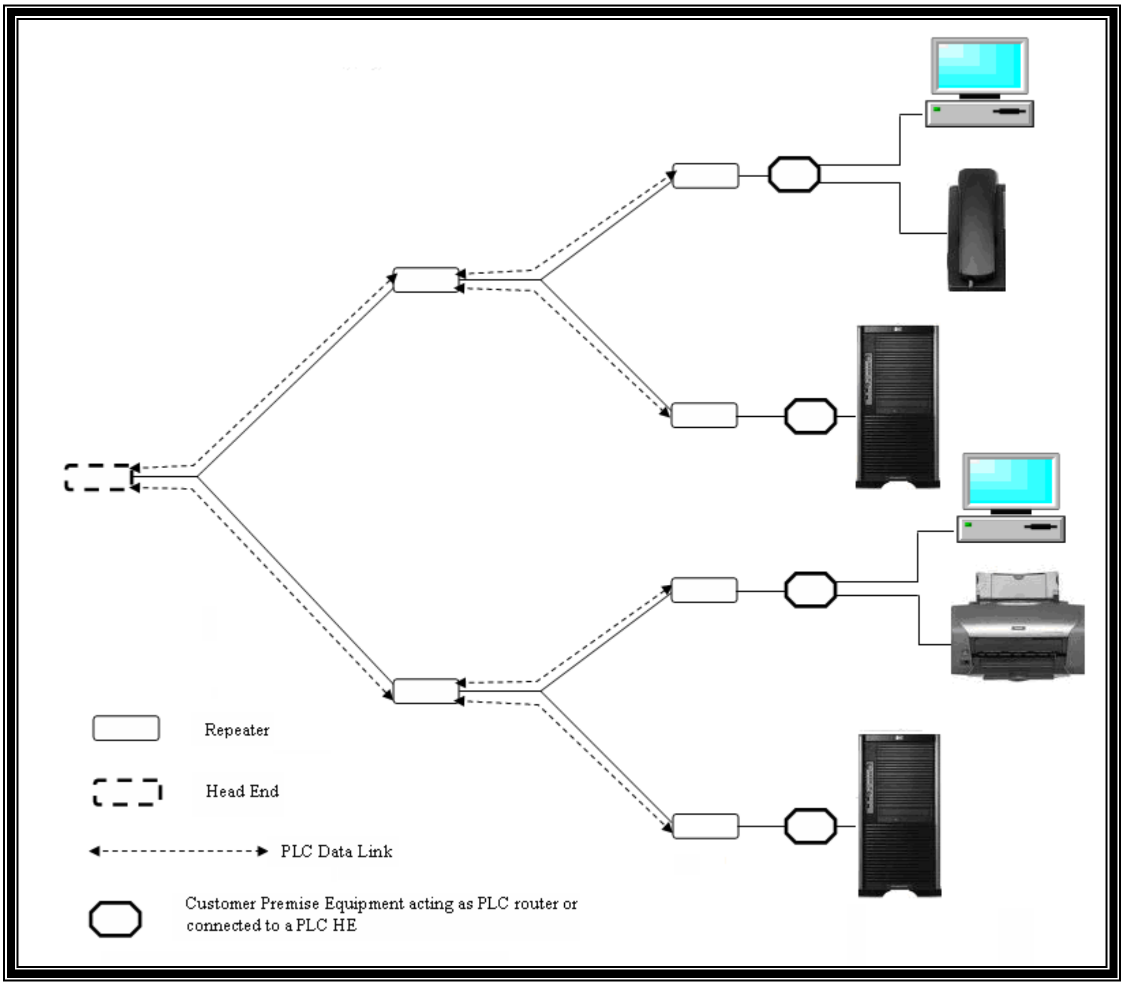

Figure 3.17: Proposed PLC Topology Model for Office End Users

3.3.3.3 Proposed Local PLC Model for Mixed End Users

The hybrid model is a topology proposed for mixed environment in which home users and professional users may reside or share the same building [Dooley01]. In other words, the hybrid topology model in Figure 3.18 is a design that caters for a situation where there is coexistence of both home users and office users on the same PLC network.

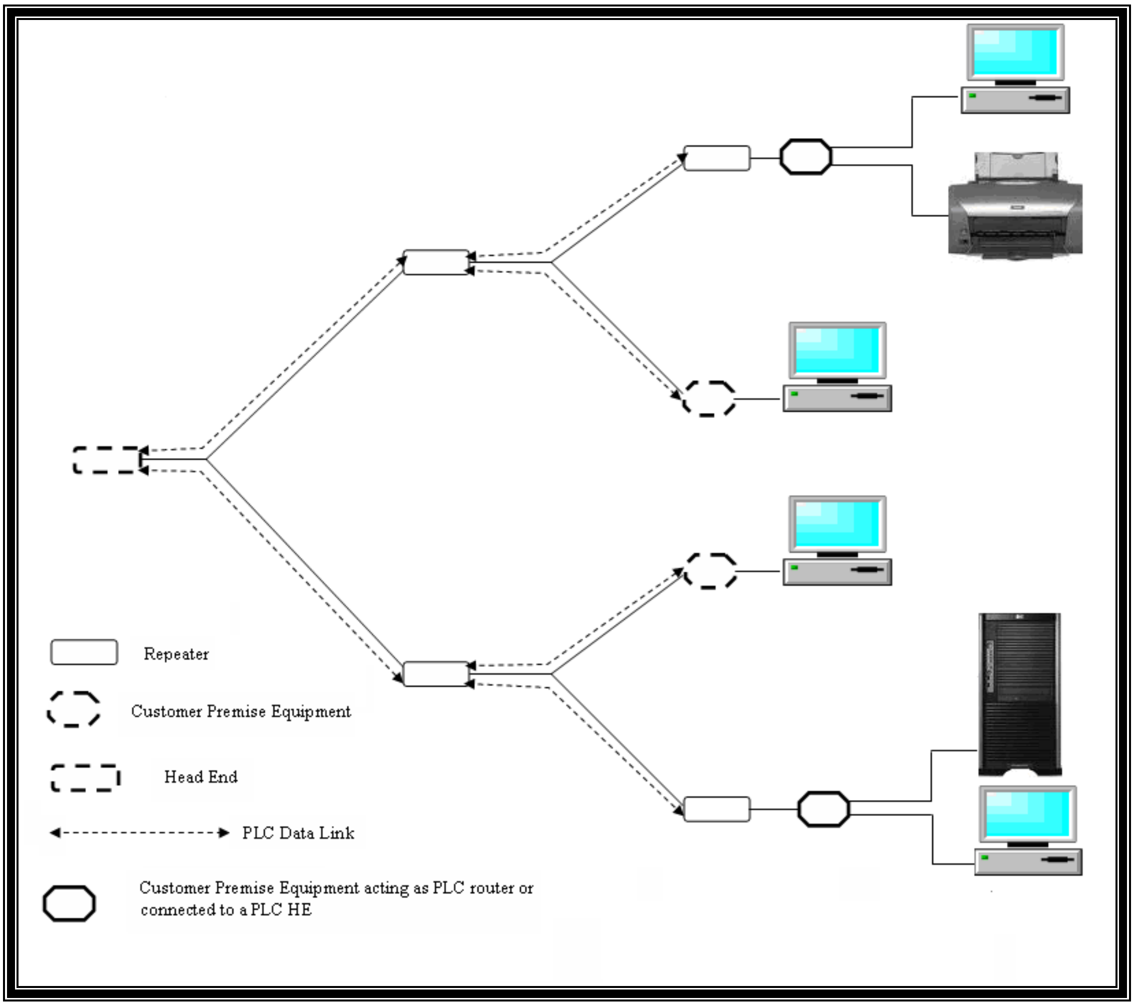

Figure 3.18: Proposed PLC Topology Model for a Hybrid Set-Up

The proposed topology for the hybrid/mixed set-up has a general structure presented in Figure 3.18. Such an environment comprises a mixture of home user and professional user requirements. The office users are very likely to have their own networking equipment such as routers and also they manage their own internal PLC networks. The home users primarily depend on the auto configuration of their network terminals and rely on the support from the network operator [Beamud *et al* 03], [Lopez04]. While on the other hand the skilled user can pretty much, handle their network. Thus, in this specific mixed environment, the research recommended using CPEs bridges for home users and customer owned PLC routers for the professional users.

3.4 Conclusion

The potential of PLC as a data networking technology is huge, but without sound or defined deployment methodologies, its growth is stifled. Therefore, this chapter has proposed and presented broadband MV and LV PLC methodologies. For different proposed MV and LV methodology solutions, different PLC network design aspects were examined. The MV, LV architecture based and LV requirement based deployment methodologies were discussed. The chapter has also analyzed and proposed different LV requirement based methodologies for different user settings. For these set-ups, suitable subsets of network topology designs were identified and discussed for each situation encompassing both residential and office grids. The chapter has presented the designing of MV and LV broadband PLC network deployment methodologies whereas the experiments, configurations and deployments of LV broadband PLC in laboratory and multi-building environments are dealt with in the following chapter.

Chapter Four

Implementations and Experiments

This chapter describes the experiments conducted to analyze and evaluate broadband PLC performance in three different experimental network configurations. The experiments investigate the performance of PLC in different data volumes file transfer scenarios. The experiments were conducted in laboratory and multibuilding LV environments. The objectives and differences between laboratory and multibuilding experiments are defined and presented. The tools, file transfer scripts and file creation scripts used in the experiments are described. The experiment scenario built for each experiment is illustrated, including description of the experiment methodology, hardware and software configurations for each set-up. This entire chapter demonstrates the applicability of broadband PLC in different proposed configurations.

4.1 Objective of the Experiments

All broadband technologies are beneficial to users if their network bandwidth can be efficiently utilized. Therefore it is important to conduct performance studies, such as transfer time and throughput measurements, of network applications executing over these networks. While software simulations can provide valuable input in the experimentation process, it is crucial that the physical system be tested under realistic traffic loads. The experiments on PLC utilize traffic patterns that closely mirror the expected user traffic load. The approach that was implemented in this research was testing PLC in three experiment set-ups for file transfer traffic. The main objective of the experiments is to give and gain insight into how PLC performs for file transfer traffic loads of variable sizes.

At the end such investigations will enable informed deductions to be made as to whether PLC can provide adequate throughput to meet requirements of demanding applications. In other words, the tests were undertaken to demonstrate the applicability of broadband PLC and how it competed with other existing broadband technologies such as Ethernet LAN. At the same time, the experiments are undertaken to analyze how PLC throughput values compare to those of known broadband technologies such as Ethernet LAN. An important consideration taken was not just the maximum available throughput, but also the application transfer time that PLC can achieve in varying configurations.

There are many different parameters for measuring traffic quality data communication network. These parameters vary for different types of services intended for the data network. We will start by describing the traffic measurement parameters used in this research.

- Bandwidth (BD) is defined as the number of bits the communication channel can transmit per second [Tanenbaum03]. The provision of bandwidth for an application means the network has sufficient capacity to support the application's throughput requirements, measured in packets per second.

- Throughput is defined as the rate at which the network receives data [Dooley01].

Throughput is a good measure of actual channel capacity. The throughput is an analogy to the load a truck can carry, and the latency or speed is how fast the truck can drive to deliver the load from point A to point B [Stallings04]. The speed is directly related to the latency of the channel. In our experiments, we calculated the throughput using the following equation (4.1) [Halsall96].

$$(E2E)\,\text{Throughput} = (S_T / T_T) \tag{4.1}$$

Where:
E2ET is the end to end throughput (bps),
S_T is the transfer size (bit),
Tq being any queue or processing time (sec),
$T_T = RTT + S_T/BD + Tq$ transfer time, in second (in reliable TCP connection with prior request message)

- Latency is the transfer time, composed of propagation time, queue or processing time and transmission time. The average transfer time was calculated from the measured times between when the connection is established until it is closed, using the equation (4.2).

$$\frac{1}{n}\sum_{i=1}^{n}(t_{ri} - t_{si}) \tag{4.2}$$

Where:
i is the packet number
n is the number of packets
t_{si} is the initial recorded time
t_{ri} is the last time recorded when the last file frame is received

- Standard deviation is defined as the square root of the variance. Standard deviation, being the square root of that quantity, therefore measures the spread of data about the mean, measured in the same units as the data [Varberg *et al* 06]. Stated more formally, the standard deviation is the root mean square deviation of values from their arithmetic mean. It helped us to measure how widely spread the values in our throughput and delay data sets were. If many data points are close to the mean, and then the standard deviation is small; if many data points are far from the mean, then the standard deviation is large. If all the data values are equal, then the standard deviation is zero. The following equation (4.3) shows standard deviation formula

$$\sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \overline{x})^2} \tag{4.3}$$

Where:
$\{x_1, x_2, \ldots, x_N\}$ is the sample
$\overline{x}$ is the mean of the sample
N is the number of degrees of freedom

- Whereas the mean is a way to describe the location of a distribution, the variance is a way to capture its scale or degree of being spread out. The unit of variance is the square of the unit of the original variable [Varberg *et al* 06]. Variance is the average of the squared differences between data points and the mean. The following equation (4.4) shows the variance formula where *N* is the sample size and $\overline{x}$ is the sample mean.

$$\frac{1}{N}\sum_{i=1}^{N}(x_i - \overline{x})^2 \tag{4.4}$$

Where:
$\overline{x}$ is the mean of the sample
N is the sample size

The throughput and delay results as will be explained in Chapter 5 were analysed using standard deviation and variance. This made it possible to analyze the extent PLC would handle different traffic loads before performance is negatively affected. In addition this enabled the understanding of how PLC compares with other broadband networks, in particular Ethernet LAN. This research is important in that it provides an independent study for the throughput of file transfer over possible home and offices PLC configurations. As will be explained in section 4.7 a file creation script was developed and was used to create files of specific sizes together with a transfer script which was then used for transferring files across the experimental networks. The following section presents the hardware and software configurations implemented and utilized in all the experiment configurations.

4.2 Experiment Hardware and Experiment Environment

4.2.1 Hardware used for the Experiment

For the purpose of the experiment, the definitions and characteristics of the PLC elements or components utilized are summarized in this section. The commercial 2nd Generation Mitsubishi PLC technology was selected as the experiment equipment. This technology supports data, video and voice applications. PLC Mitsubishi 2nd Generation supports very high bandwidth which allows up to 200 Mbps over a distance of 300m. The technology package comprised the Mistubishi frequency division repeater (FD), capacitative coupling units (CCU) and customer premises equipment (CPE). The FD repeater consists of two Time Division (TD) LV cards repeaters that are connected together to perform a frequency division transmission [Mitsubishi03]. Its role was to regenerate the PLC signal for better coverage on the low voltage (LV) network and relaying communication signal between neighboring customer premises equipment units within the experiment setup.

Some general Mistubishi Frequency Division (FD) Repeater specifications:

- Physical speed: Max 200Mbps
- Installation type: wall mount in a meter room or meter box
- Interface: 1× Dsub9 female connector for PLC signal connection
  1× Dsub9 male connector for maintenance
- Dimension & Weight: Dimension 80mm [W] * 320mm [H] * 180mm
  Weight: Approximately 8kg
- Operating Condition: Temperature 0 to 60 degree Celsius with fan and Humidity 0 to 95%
- Power supply: +90V to +265V
- Power Consumption: 30W
- Other features: High reliability under high temperature
  Low noise and low power consumption

The FD node acted as the master node, managing communication within the PLC experiment segment. In other words, it was used to control, distribute and refresh signals between the CPEs [Hrasnica *et al* 04]. The University of Fort Hare LAN was used as the backbone network. The PLC segment was bridged to the backhaul network via the FD repeater node. The FD master node was connected to the backbone network through the respective port on the FD back panel. On the other side, the FD node was coupled to the LV grid using a system of Mistubishi capacitive coupling units (CCU). By using the low voltage CCU, the PLC signal would be efficiently and safely injected into the LV grid. CCUs are used to transmit/receive modem signals from the LV grid and offer an inexpensive and easy installation solution, which guarantee efficient signal injection without interrupting the energy of the LV network [Mitsubishi03].

Some general Mistubishi LV-Capacitive Coupling Unit (CCU) specifications:

- Model: CCU-212-C0
- Maximum Rating: 420VAC
- Line Frequency: 45 to 65Hz
- Dimension & Weight: Dimension: 70(W) x 40(D) x 25(H) [mm](Main unit)
- Operating Condition: Environmental Temperature -10 to 60 degree Celsius
  Humidity: 0 to 90%RH (non-condensing) Indoor use only.
- Surge Resistance: 3000A (8/20μs)
- Material Body: polystyrene, Mold: epoxy resin LVCCU

Two commercial Mitsubishi PLC LV modems with a physical speed of 200Mbps were selected as end-user equipment. The modems are designed for indoor use, and are able to operate in single-phase indoor distribution networks with 50 Hz mains voltage. The CPE function is primarily for PLC network access from users' computer. The modems supply broadband connection, via Ethernet or USB interfaces allowing high transmission speeds including data transmission with the Internet [Mitsubishi03].

Some general Mistubishi Customer Premises Equipment (CPE) specifications:

- Physical speed: Max 200Mbps
- Installation type: Installed in a home
- Interface: 1 Ethernet port (RJ45)
  With USB port (USB 1.1)
  Link quality indicator (4 LEDs)
- Dimension & Weight: Dimension: 47mm [W] * 154mm [H] * 194 mm [D]
  Weight: Approximately 0.7kg
- Operating Condition: Temperature 0 to 45 degree and Humidity 0 to 95%
- Power supply: +90V to +265V
- Other features: No external AC adapter, coupling unit
  Remote firmware upgrade

The hardware facilities used also included Proline Pentium IV 3.40 GHz computers equipped with 1.00 GB of RAM that were used as severs and as the end-user systems in the three different experiment configurations. The Proline computers were selected because they are capable of sustained and significant TCP/IP transfer rates. The basic structure of the PLC testbed utilized in all the experiment configurations in this research is presented and discussed in the following section.

4.2.2 Characteristics of the PLC Testbed and Laboratory Environment

The Computer Science Department at Fort Hare University maintains a PLC testbed in the Masters Laboratory that is used to perform measurement studies and conduct a variety of network experiments. The testbed is a low voltage indoor network constructed to work as the PLC master node. The following Figure 4.1 illustrates Computer Science (CSC) Laboratory environment where PLC was implemented.

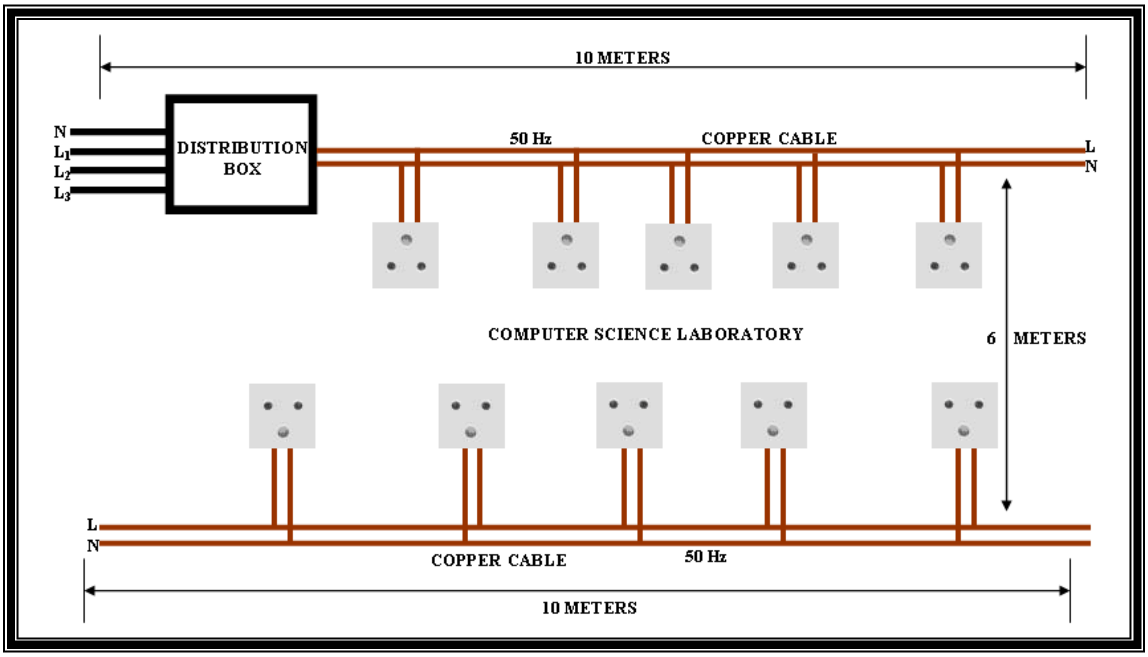

Figure 4.1: Diagram showing CSC Laboratory Layout.

As depicted in Figure 4.1 the CSC Laboratory was the point of PLC signal injection into the LV grid. The testbed (meaning the entire PLC network) environment was constructed using the commercial 2nd Generation Mitsubishi Electric PLC devices mentioned previously in section 4.1. It should also be noted that the CSC Laboratory is located in a campus environment. The frequency division node is installed in the CSC Laboratory, as will explained and shown later. It is connected on one side to the University of Fort Hare LAN network (as the backbone network) and on the other side it is coupled to the low voltage grid. Thus it converted packets generated from the LAN network into the PLC compatible packets, and vice versa. This set-up was the PLC master node and it was utilized as such in this research.

As indicated in Figure 4.1 the CSC Laboratory in which most of the experiments were carried out measures approximately 6 m x 10 m. The laboratory housed at the time of the experiment 19 operating computers and other peripheral devices shared the same electrical mains with PLC. During the tests it was ensured that all the other computers and devices using the low voltage electrical grid do not generate considerable traffic or load while experiments were being conducted. Due to the structure of network set up, the effects of individual components on the characteristics of the experiment were possibly observed. All the experiments were conducted on an unloaded network meaning that communication was minimized by leaving communication to those computers involved in the experiments.

4.3 Experiment Software Configurations

4.3.1 Open Source Software

All the experiments were executed and investigated on a free and open source software (FOSS) platform. Linux Ubuntu version 6.10 was selected as the platform for our experiments and was installed with the least of problems. This was done in regard to the goal of CoE research and additionally for the purposes of cost effectiveness. The dynamic host configuration protocol (dhcpd) server and the file transfer protocol (ftp) servers implemented in this research were all open source software modules as will be explained in the following section.

4.3.2 Dynamic Host Configuration Protocol Daemon

The dynamic host configuration protocol daemon (dhcpd) server was developed by Internet

Software Consortium. The dhcpd allowed computers within the three experiment scenarios to request and be assigned IP addresses, and to discover information about the network to which they were attached. The dhcpd server allows a host, which is unknown to the network administrator to be automatically assigned a new IP address out of a pool of IP addresses for its network [Lemon02]. In order for this to work, the computers in each experimental network were allocated addresses and these were entered into the dhcpd configuration file. On startup, dhcpd read the dhcpd configuration file and stored a list of available addresses. When a client requested an address using the DHCP protocol, dhcpd server allocated an address for it. Again, as was the case with the compilation and installation of the Linux operating system, the set up for the dhcpd server was without any installation irregularity.

4.3.3 FTP Server Daemon and FTP Client

The file server used in this research was a proftpd daemon version 1.3.0. It is a Linux compatible ftp server, the latest version available at the time of writing. Proftpd stands for professional file transfer protocol daemon (Proftpd) [Lowes01]. It is a professional configurable secure file transfer protocol server. It is a full featured replacement for the standard supplied by most Linux vendors supporting the ftp protocol. Proftpd is a popular ftp daemon used on many ftp sites and the source code is freely available. The Proftpd server may be invoked by the Internet "super-server" (`inetd`) each time a connection to the ftp service is made, or alternatively it can be run as a standalone daemon [Lowes01]. The standard Proftpd was complied without any incompatibilities. The Proftpd was utilized in a standalone mode with a known username and password. The Proftpd server was configured at the start up time using the configuration files that specified the necessary execution parameters such as the root directory and default port number.

On the client side a free non-interactive `Wget` version 1.10.1 utility was implemented. GNU `Wget` is a free open-source command line program that allows transferring of files. It was utilized within the transfer scripts without any problems. It is licensed under the terms of the General Public License (GNU) [GNUWget05] and supports http, https, and ftp protocols. It allowed for the development of transfer scripts to transfer files across all experiment set-ups. `Wget` can work in the background, while the user is not logged on. This allowed the transfer scripts to start file retrieval and disconnect from the system, allowing wget finish the work. `Wget` has been designed for robustness over unstable network connections; if a transfer fails due to a network problem, it will keep retrying until the whole file has been retrieved [GNUWget05]. `Wget` supports connections through proxies, allowing one to use it in an environment that can access the internet only via a proxy. The `Wget` program compiled and installed with ease and was compatible with proftpd server. The `wget` program accepted commands from transfer script files, which automated the login process and the file transfer as will be described in section 4.6 on file transfer script development. The following section present ftp characteristics and the reasons why we used ftp protocol for this research.

4.4 Investigation using the File Transfer Protocol (FTP) Application

The ftp protocol has been selected for our experiments because it constitutes what is considered to be one of the most frequently used network application [Brecht98] and is extremely likely that the use of this protocol has substantially increased. We used it for our experiments because it is an open standard and widely deployed in almost every operating system. Above all ftp is well documented and broadly accepted as the de facto data transfer mechanism available in modern software [Bhush *et al* 00]. The classic file transfer protocol defines the capability for clients to send data to servers using the underlying TCP/IP protocol. Its primary function is to facilitate transfer of files between hosts, and to allow convenient use of storage and file handling capabilities of other hosts [Postel *et al* 85]. As depicted in Figure 4.2 ftp operates in a client/server approach and uses two TCP port connections, one as a command channel and the other is for data transfer allowing it to simultaneously issue commands and transfer data between the client and server.

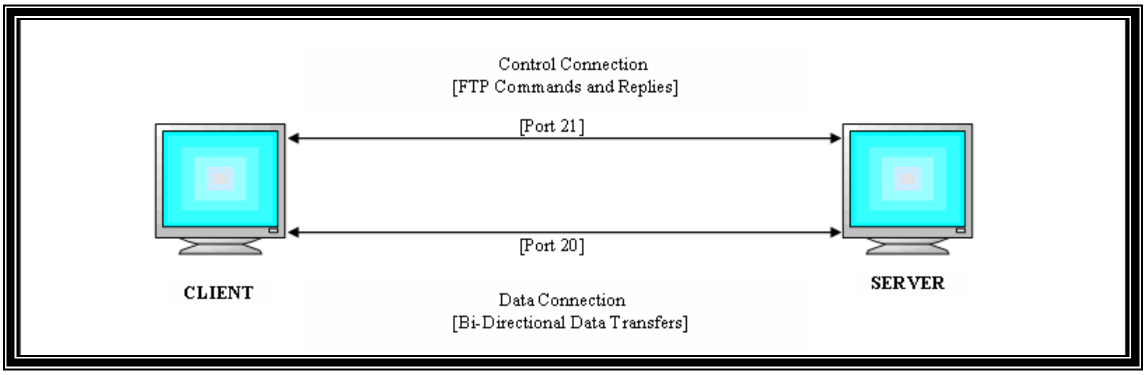

Figure 4.2: A typical FTP Client/Server Scenario.

The client sends ftp commands and interprets replies received. The server interprets commands, sends replies and when necessary sets up data connections and transfers data. The client listens on the data port prior to sending a transfer request command. The client's default data port is the same as the control connection port. Upon receiving the transfer request, the server initiates the data connection to the port. When the connection is established, the data transfer begins and the server sends a confirming reply to the client after which the server then closes the connection [Brecht98]. The development followed for the transfer script is explained in the next section.

4.5 Transfer Script Development and Description

The script that performed the transfer of files was developed using Bash an acronym for Bourne Again Shell programming, which is a Linux based scripting language [Cooper06]. The use of bash programming has become a de facto standard for shell scripting on all flavors of UNIX systems [Cooper06]. The script performed standard file transferring procedures from one machine to another with zero errors. The following instance in Figure 4.3 depicts the transfer script written for transferring the files across the experimental configurations.

```
#!/bin/bash

/usr/bin/time  -p  -a  -o  ftptime.log  wget  --ftp-user=powerline  --ftp-
password=powerline  ftp://172.20.56.104/500B  --append  ftpstatistics  -rm
500B*
```

Figure 4.3: Downloading or Transfer Script.

For the transfer script to record the time of the file transfer, the `time` function was called before any data was read from the file server. It was called again immediately after all the data was stored on the client node. The elapsed time was then calculated. The measured time spanned the entire data connection from connection to the termination of the transfer process. To measure the transaction time in a more accurate way the script operates in such a way that it waits for all the data to arrive and for the connection to close before calling time function for the second time. The transfer time statistics were directed and appended to the `ftptime.log` with argument -o standing for output file. The script was provided with `--ftp-username` and `--ftp-password` to automatically log onto the server. The transfer output was appended to a designated file `ftpstatistics` then the transferred file was deleted by the `–rm` option.

The transfer script worked as follows: first read the content into the buffer then fetch the content from the buffer and write to disk after that verify that the whole data in the buffer has been written then give a success message. The script allowed us to experiment with different file sizes evaluating how the performance of each experiment configuration was affected. For each connection, the output returned showed the current transfer speed and time usage statistics. The script used `–a` or `–append` as the argument for appending to an output file. On every execution, the transfer output was appended instead of being overwritten to the `ftpstatistics` output file. Ten scripts for each file were loaded into the `cron.daily` directory as shown in the following two examples in Figure 4.4 and Figure 4.5

```
root@powerline-desktop:/etc/cron.daily# ls
ftp500Bscript ftp5KBscript ftp10KBscript ftp500KBscript ftp5MBscript
ftp15MBscript ftp25MBscript ftp50MBscript ftp75MBscript ftp100MBscript
```

Figure 4.4: All File Transfer Scripts.

```
root@powerline-desktop:/etc/cron.daily# cat ftp500Bscript
#!/bin/bash
/usr/bin/time   -p   -a   -o   ftptime.log   wget   --ftp-user=powerline   --ftp-
password=powerline ftp://172.20.56.104/500B --append ftpstatistics -rm 500B*
```

Figure 4.5: Script File Configuration cron.daily Directory.

The dedicated transfer script was designed with an attribute of initiating automated multiple file transfer transactions or processes from different sources and to the same destination host (file server). The advantage of this is that results consume less of the system resources and it was a useful feature in observing the transfer behavior across connection paths in each experiment configuration. The scheduling of these multiple file transfer streams was done using the `cron` mechanism, which is a powerful task scheduler available in Ubuntu Linux it allows the execution of commands at specified times. We used the `cron` utility to schedule and automate the execution of the transfer script tasks. The configuration of the `cron` utility involved setting up and defining parameters in the `crontab` file. The `crontab` file has five fields for specifying day, date and time followed by the command to be run at that interval. By defining items in `crontab`, we were able schedule the transfer scripts for each file to run on scheduled time interval. The configuration was set up by specifying the time at which the required transfer scripts were to be executed. By editing the `crontab` file using the command `crontab –e` the transfer scripts were configured to execute at a specific time in the month of September and October 2007 for a week in each experiment configuration. The `cron` execute crontab configuration file shown in Figure 4.6 called a file inside `cron.daily`, checked the existing transfer scripts (they were ten scripts for each file), and executed them at the specified time. The `crontab` file was listed as shown in Figure 4.6 using the command `crontab –l` and it was configured using the command crontab -e.

```
root@powerline-desktop:/etc/cron.daily# crontab -e
* 13    09 * *        run-parts --report /etc/cron.daily
```

Figure 4. 6: Crontab File Configurations.

The scripts allowed the researcher to transfer files from the file server while recording the entire data connection, beginning from the establishment of the data connection to the completion of the data transfer on the client side. All server-oriented output remained at the file server console and all client-oriented output remained on the client console. This approach had the advantages in that the implementation of the file server was made less demanding. Because the output of the client and server were independent this made scrutiny of the transfer scripts output manageable. Therefore, the output was adjustable and more flexible in each experiment set-up.

In this research the developed transfer script proved useful and powerful as a measurement program because it provided a way of quantifying how fast the files were transmitted over the three different experiment environments. In addition, the output statistics from the transfer script made it possible to make comparative analysis between PLC and Ethernet. Above all the transfer scripts developed allowed us to experiment with different file sizes and observe how those different files affected transfer time and throughput behavior of each experiment configuration. These will be explained in the following section.

4.6 Creation of Files of Specific Sizes using Bash Programming

There was a need for creating files, since one of the foremost reasons was investigating and understanding PLC performance in file transfer using timing file transfer scripts. Files of specific sizes were created to have better investigation and understanding of how sensitive the experiment scenarios were to files of variable sizes. The script that created files of specific sizes was developed using bash programming. The files were then used to investigate exhaustively how different experiment setups reacted to file transactions as the file size increased. The script is illustrated in Figure 4.7.

```
root@powerline-desktop:/home/powerline# dd if = /dev/zero of = filename count =
10000;
```

Figure 4.7: Script used to create files of varying sizes.

In the script parameter declarations we employed the data definition (`dd`) Ubuntu Linux utility. The `dd` parameter reads from its standard input and writes to its standard output, unless programmed to follow certain specifications. In Figure 4.7 we specified in the script the input file name as the standard input default using if argument which stand for input file. A special file called `/dev/zero` present in Unix-like operating systems was used as the input file for our script. The file `/dev/zero` declared in the script provide as many null characters as are read from it. These were used to generate clean files of specific sizes for this research. The argument of in the script specified the output file name to which the bytes of certain block sizes were written. Argument count specified the block size, in other words the file size.

The script read the input file `/dev/zero`, did the specified conversions, and then copied the converted data to the output file `filename`. The input and output block sizes were specified. The term block refers to the quantity of data read or written by the script in one operation where sizes are specified, and then a number of bytes are expected indicating the output size. The `count` argument specified bytes for file size; the bytes were then converted and copied to the output file `filename`. In essence, the script copies and optionally converts data. It uses an input buffer, conversion buffer if conversion is specified, and an output buffer. Reads are issued to the input file or device for the size of the input buffer, optional conversions are applied, and the size for the output buffer is issued. This allows input and output requests to be tailored to the requirements of a task. It directs the output to the standard error, which reports the number of full and short blocks read and written.

The script created ten files by modifying the `count` parameter for each file size. The created files were 500B, 5KB, 10KB, 500KB, 5MB, 15MB, 25MB, 50MB, 75MB, and 100MB. These files were made to be larger than the expected. This was done so to push the experiment configurations to higher usage levels in order to observe how they deal with the intensity of handling larger files. The assumption behind this is that if the system can handle the larger files efficiently then it would be able to handle normal usage and to scale to higher usage levels without performance degradation. In turn these ten files were then loaded on the server through the transfer script developed in section 4.6 was then employed to transfer the files across the network. At the same time, transfer script monitored the throughput and time usage of each transfer process across the three different experimental network set-ups from the server to the client. The following sections elaborate the tests and characteristics that comprised each of the three experimental environments that were configured for this research.

4.7 Outline of the Data Transfer Experiments

To conduct the experiments three network set-ups were designed to measure the achievable transfer time and throughput of each of the environments considered. First and second experiments conducted were in a laboratory environment. Two network set-ups were installed, tested, and verified in a controlled environment with as little network disturbance as possible. All the tests were conducted with network communication minimized except computers involved in the experiments. The third experiment set-up was implemented and tested in a multibuilding setting. The experiment sequence consists of following three phases:

- Experiment One: Laboratory Data Transfer in a PLC Environment
- Experiment Two: Laboratory Data Transfer in a Mixed Client Environment
- Experiment Three: Multibuilding Data Transfer in a PLC Environment

The LV First Model for Home User (Chapter 3, Figure 3.12) was followed when we designed Experiment One. In Experiment Two, Hybrid Set-up Model (Chapter 3, Figure 3.18) was found suitable; we constructed the experiment in such a way that instead of mixing home and professional users we mixed the broadband PLC and Ethernet LAN technologies. Experiment Three was designed closely following the Second Model (Chapter 3, Figure 3.13) proposed for the Local PLC Topology Architecture. Transfer time and throughput, were measured using exactly the same files. The type of clients, number of clients and distance were the testing components that were altered in each experiment set-up. The following sections illustrate and explain in detail the experiments constructed.

4.7.1 Experiment One: Laboratory Data Transfer in a PLC Environment

For this experiment, two computers were configured one as a PLC server and the other one as a PLC client node in a in laboratory environment In this configuration PLC was connected to the frequency division (FD) repeater and which was in turn coupled to the LV grid as indicated in Figure 4.8.

4.7.1.1 Experiment Configuration and Methodology

The server(s) and client(s) were placed in the Masters Computer Science Laboratory. The experiment configuration consisted of two Proline 3.40 GHz Pentium IV machines with 1.0 GB of RAM and had Ubuntu Linux 6.10 installed. The computers were connected to the PLC network via the same power strip to give an almost ideal powerline channel. One machine configured as a client and the other was implemented as an ftp server. Both computers were connected to separate Mistubishi CPEs, which in turn connected them to the PLC network. The PLC client machine communicated with ftp server through the Mistubishi FD repeater. The FD node handles all the relaying of the communication signal and the management of the PLC network. The following experiment structure in Figure 4.8 was implemented for the tests.

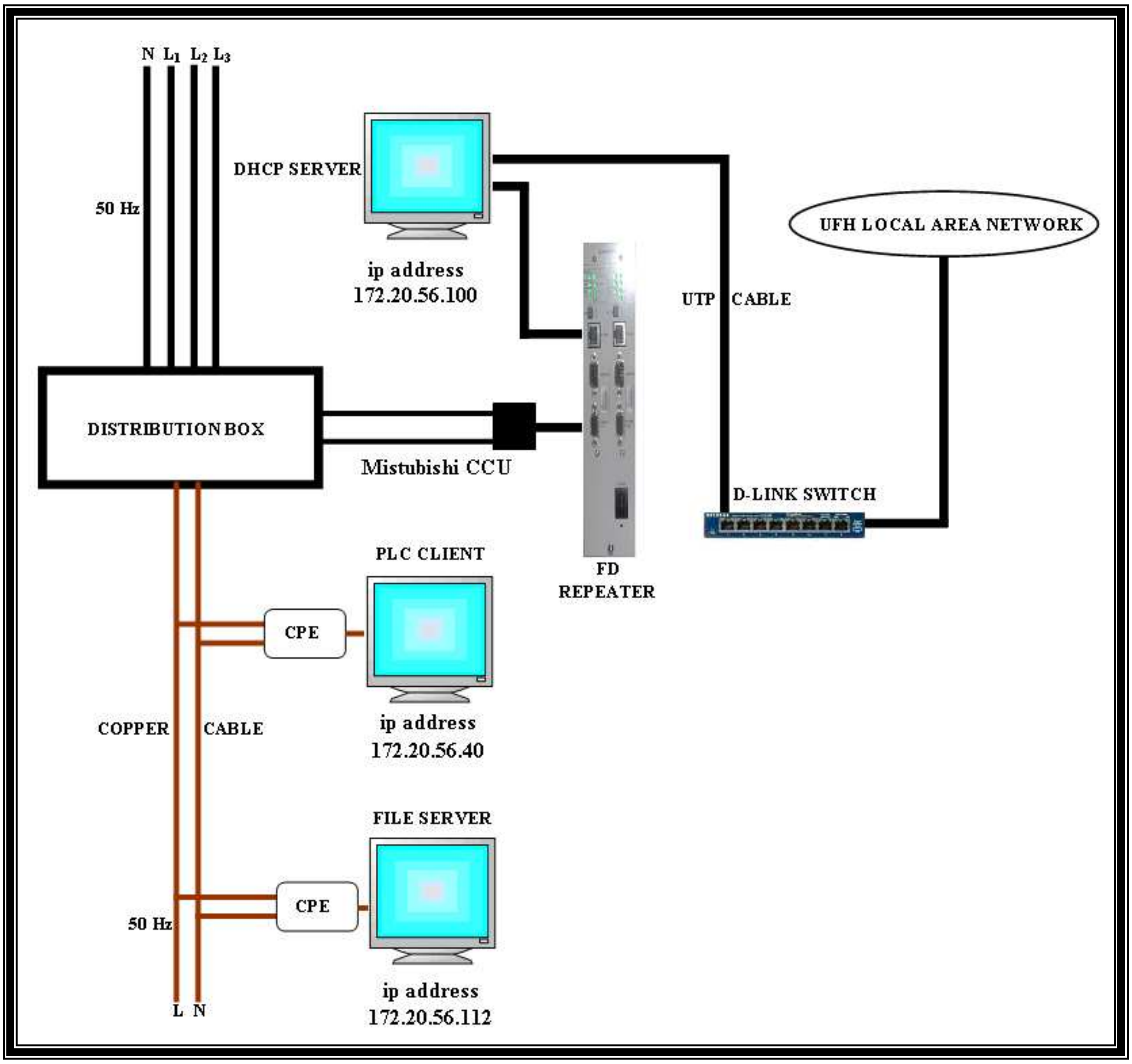

Figure 4. 8: Experiment One: Laboratory Data Transfer Configuration.

The server and the client were installed with a distance of 10 m between them. IP addresses 172.20.56.40 and 172.20.56.112 were assigned to the client and the server respectively, the very moment they were connected to the network. During the experiment traffic load on the network was minimized to the computers executing the transfer tests. As previously explained in section 4.7 ten files of varying sizes were created and loaded onto the proftpd server. The varying file sizes were chosen to minimize hardware uncertainty and human error. The PLC client requested files one at a time from the server over the PLC network. During each ftp transaction execution, the ten files were each transferred utilizing the transfer script presented and discussed in section 4.6. In all the transfers, under this section, the files were retrieved and measured individually. In other words, the client requested and accessed the server and transferred one file at time.

The transfer script recorded the transfer statistics of each file retrieved from the server during each transaction. The transfer script directed the output statistics of each transfer to the output file `ftpstatistics` on the client machine. These file transfer measurements were done and the statistics taken on a daily basis from Monday 10th to Friday 14th September 2007. The downloading requests were initiated by the client machine using the `cron` mechanism. This allowed the transfer to start at specified times as explained in section 4.6. This experiment has real-world significance in that it provides raw performance metrics of how well the PLC network is able to handle and support network applications such as file transfer.

4.7.2 Experiment Two: Laboratory Data Transfer in a Mixed Client Environment

This section presents an experiment configuration that examined the comparative performance of PLC and Ethernet LAN. The experiments were done in a laboratory setting. The experiment measured the same variables as previously explained in Experiment One section 4.9. The server was connected to the University of Fort Hare (UFH) backbone and was accessed by both the PLC node and the Ethernet node.

4.7.2.1 Experiment Environment and Methodology

The first experiment configuration was modified for the second experiment, in that, file transfer requests were now from two nodes of different technologies. Of the two client machines, one client node was set up on the PLC network and the other client node on the Ethernet network. The client implemented as an Ethernet node was connected to the UFH LAN network. The PLC CPE was connected to the USB port of the computer and to the AC power outlet. All the computers used in the experiment were Proline 3.40 GHz Pentium IV machines, running Ubuntu Linux 6.10. To compare PLC and Ethernet, the ideal experiment set-up was designed as illustrated in Figure 4.9 below.

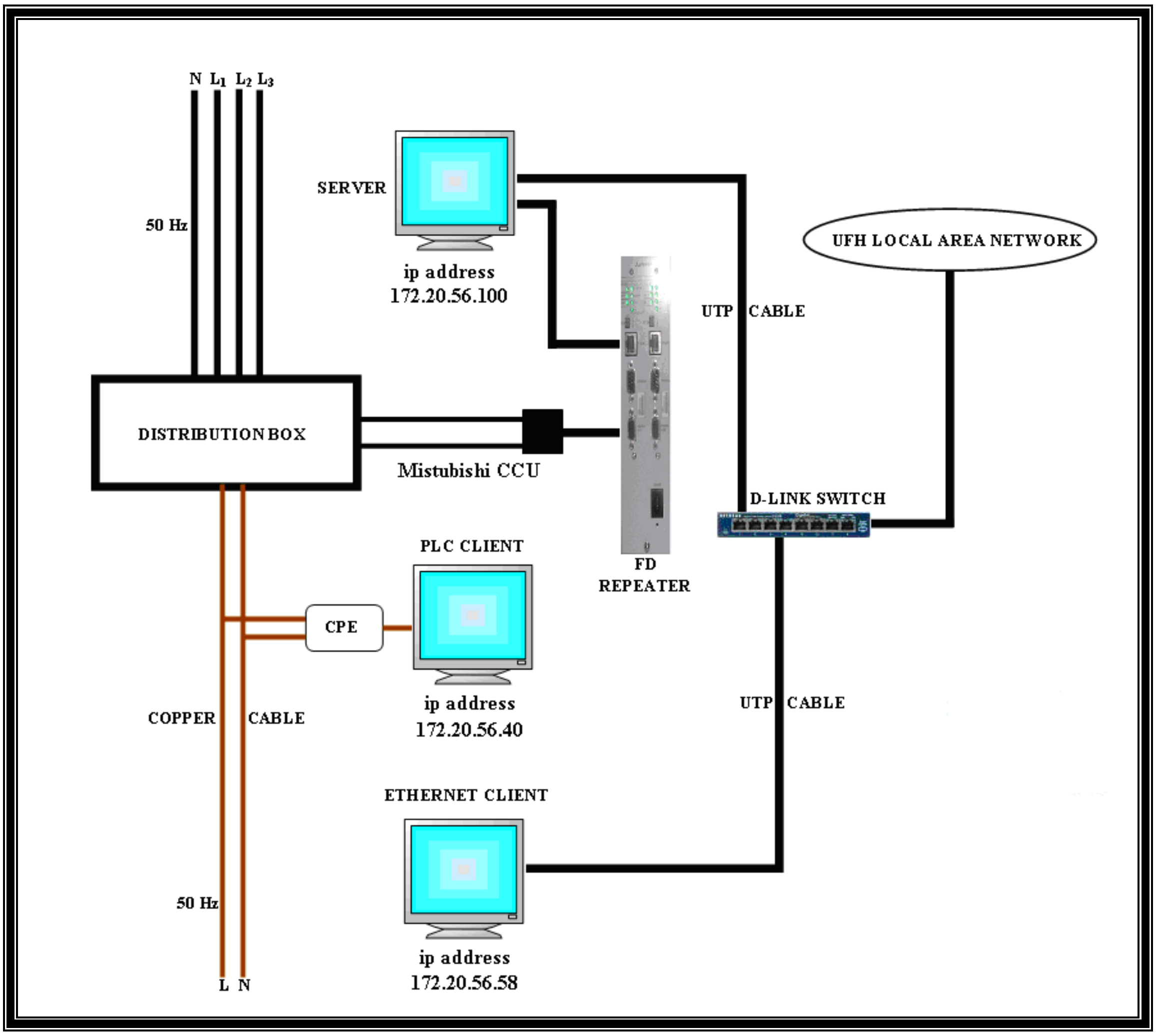

Figure 4. 9: Experiment Two: Laboratory Data Transfer Configuration.

The average distance of the A/C outlet and the Ethernet LAN network point from the server was 10m. Each node was configured to obtain an IP address dynamically. When the PLC node was connected to PLC network, IP address 172.20.56.40 was assigned. On the other hand, the Ethernet node was allocated 172.20.56.58 as an IP address by the DHCP server when it was plugged to the Ethernet LAN. The tests were done in the Computer Science Laboratory with an average load equivalent to home or office scenario. The measurements were observed for a period of 5 days from Monday 10^{th} to Friday 14^{th} September 2007. Besides the operating system, there was no other major application running at the time of file transfer.

The downloading script on the client node measured both the file transfer rate and the time elapsed during each in transaction on every file. Both the PLC client and Ethernet client simultaneously initiated file transactions as defined by the `cron` mechanism. The transfer scripts measured the time and rate at which files were transferred and just as in the previous experiment, 10 files were retrieved. The statistics were appended to a designated output file `ftpstatistics` after the transfer procedure of each file. These clients were equidistant from the server. This experiment is unique from other experiments because it mixed both PLC and Ethernet clients when accessing and transacting with the proftpd server. These file transfer tests enabled us to examine the extent to which PLC compares to Ethernet LAN under the same file transaction load.

4.7.3 Experiment Three: Multibuilding Data Transfer in a PLC Environment

The experiment configuration here was designed to measure the data transfer capability of PLC in a multibuilding setting. The primary intention of this phase is to analyze the potential of PLC solution as a network system across buildings. This was done so as to have an indication of the performance of PLC as a solution for broadband services in a wider coverage. The data transfer was done between the Computer Science Laboratory (CSC) and the GIS Laboratory (GIS).

4.7.3.1 Experiment Environment and Methodology

The installation of this experiment was undertaken between CSC and GIS Laboratories where the environment had the least disturbance possible. The client node was installed in the GIS Laboratory and the server node was placed in the CSC Laboratory. The configuration in Figure 4.10 was designed and used for these multi-building experiments.

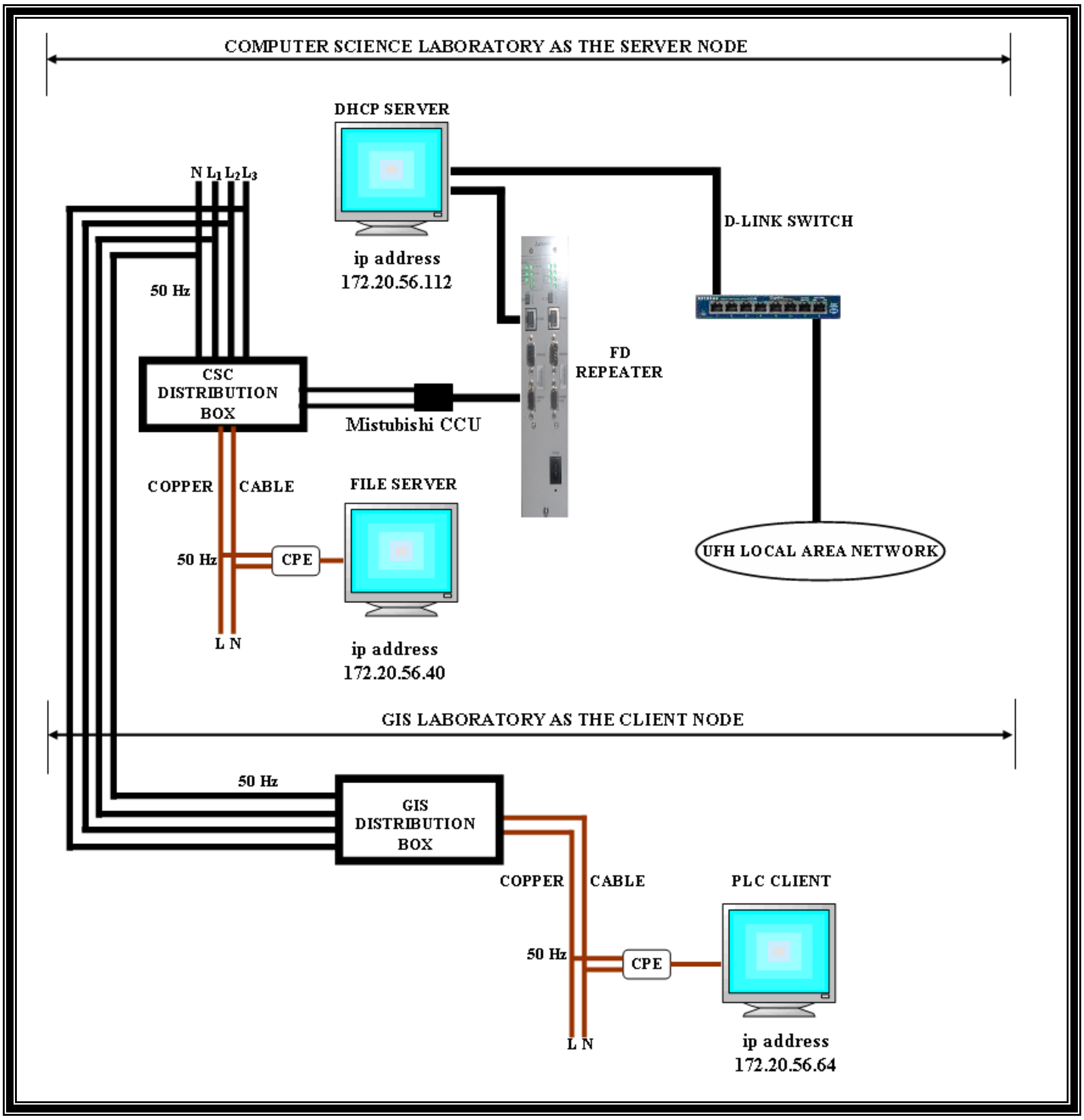

Figure 4.10: Experiment Three: Multibuilding Data Transfer Configuration.

The configuration had a distance of about 80m between the master node (in CSC) and the client node (in GIS). We executed these multibuilding experiments in the timeframe of Monday 22nd to Friday 26th October 2007. The same ten files were transferred as was done in the previous experiments. The PLC solution is expected to perform reliably in such an environment. The testing environment for collecting the performance results comprised DHCP server, file server and the client machine. All the computers were Proline 3.40 GHz Pentium IV equipped with 1.0 GB of RAM. The DHCP server and the file server were set-up in the CSC Laboratory and the client node was in the GIS Laboratory.

The test network set-up also consisted of the 2nd Generation Mistubishi Electric modules, connected to the USB interface of the computer and to the electrical socket. The operating system on all the computers was Ubuntu Linux 6.10. Each of the computer interfaces was set to obtain an IP address automatically. When the PLC CPEs were connected to the computers, the DHCP server assigned IP addresses 172.20.56.64 for the client node in the GIS Laboratory and 172.20.56.40 was allocated to the file server in the CSC Laboratory. The DHCP server was assigned 172.20.56.112 on the UFH LAN as depicted in Figure 4.10. Apart from the operating system there was no other major application running on the computers at the time of file transfer. The experiment configuration was isolated from other network traffic to ensure the accuracy of the tests.

4.8 Conclusion

The chapter has presented the setup and the successful implementation of three distinct experiments with the characteristics of each experiment environment. The three experiment configurations were:

- Experiment One: Laboratory Data Transfer in a PLC Environment
- Experiment Two: Laboratory Data Transfer in a Mixed Client Environment
- Experiment Three: Multibuilding Data Transfer in a PLC Environment

The objectives of the experimental work, hardware and software utilized in this research were discussed. The chapter also presented the development of the file creation scripts and file transfer scripts. The experiments were done under different settings and shared the same variables of measurements. This chapter has given a description and execution of all the experiments. The results from these experiments are analyzed in the next chapter, which focuses primarily on results evaluation and presentation.

Chapter Five

Results and Evaluations

This chapter presents and analyzes the results from experiments executed using 2nd Generation Mitsubishi Electric PLC Technology. The results are from three laboratory and multibuilding experiments implemented and explained previously in Chapter 4. The analysis of the results is made on the basis of transfer time taken and throughput achieved. Data were captured and computed using the mathematical equations (4.1), (4.2), (4.3), and (4.4) presented in Chapter 4, and equation (5.1) in Chapter 5. By showing a set of graphs from the experiments the chapter explores broadband PLC performance behaviour in each experiment configuration. Of interest also, is the presentation, comparison, evaluation and discussion of broadband PLC and Ethernet LAN performance results. The chapter enable deductions to be made on whether broadband PLC potential can provide adequate throughput to meet requirements of the most demanding broadband applications of today and the future.

5.1 Analytical Discussion of the Data Transfer Experimental Results

This section describes and evaluates the transfer time and throughput results of the experiments undertaken based on the measurements taken. We experimented on the practical implementation of PLC we did not measure the noise levels. The results evaluation phase collects raw data statistics and visualizes this data using a set of extensive and conclusive graphs. The raw data set consisted of outcomes of experiments executed and described in Chapter 4. The outcomes can be different each time the measurements are done. After the execution of experiments, we processed the measured data and computed the data using equations (4.1) and (4.2). The objectives of data processing were to visualize the raw data obtained from each individual measurement in each experiment in form of extensive graphs in order to facilitate comprehensive analysis and evaluation of the adequacy of PLC in the experiment settings using also equations (4.3) and (4.4).

The graphs illustrate two types of results, one set depict throughput and the other set transfer time taken by each file. Throughput is recorded in megabits per second (Mbps) and file size is shown in megabytes (MB). A total of ten files were transferred across each experiment setup. The evaluation scheme consists of 17 conclusive graphs showing results of all the experiments done in this research. We present the results for a period of 5 days per experiment configuration in the following order: graphs presenting the transfer time and throughput with data for each day, graphs presenting average transfer time and average throughput, and graphs showing the optimal load of the PLC link. This will be presented and explained in detail in the following sections.

5.2 Experiment One: Laboratory Data Transfer in a PLC Environment

The tests under this section were performed to ascertain the baseline throughput and transfer time values of PLC using a single PLC client in a controlled laboratory configuration. The study recorded measurements observed from Monday 10th to Friday 14th September 2007. A total of ten files were transferred across the network in this experiment setup. This case helped us compare performance with graphs plotted in other experiment configurations which are presented later in the Chapter. Assuming all is equal any change in the load is expected to affect the PLC performance and transfer time.

5.2.1 Discussion of Performance Experiments Results

Figure 5.1 shows data transfer time taken by each file and Figure 5.2 illustrate PLC throughput versus the file size with respect to data it can handle per second. Both Figures 5.1 and 5.2 show multiple curves, each curve is showing the transfer time and throughput behavior of the experiment setup for each day.

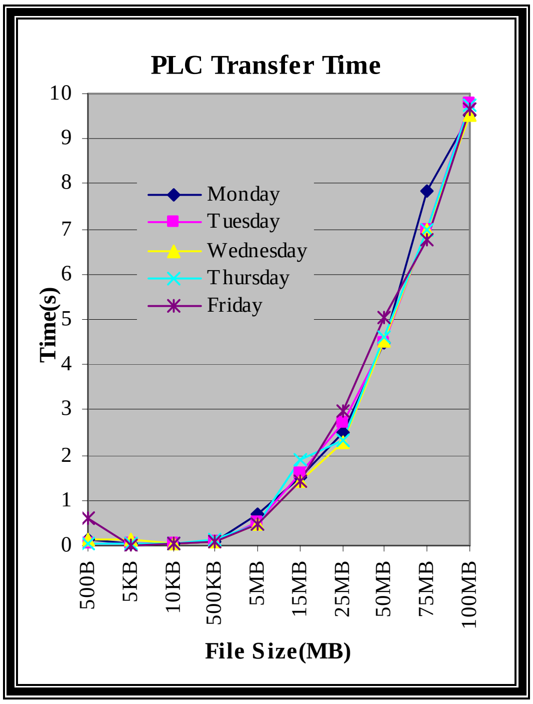

Figure 5.1: Broadband PLC Transfer Time

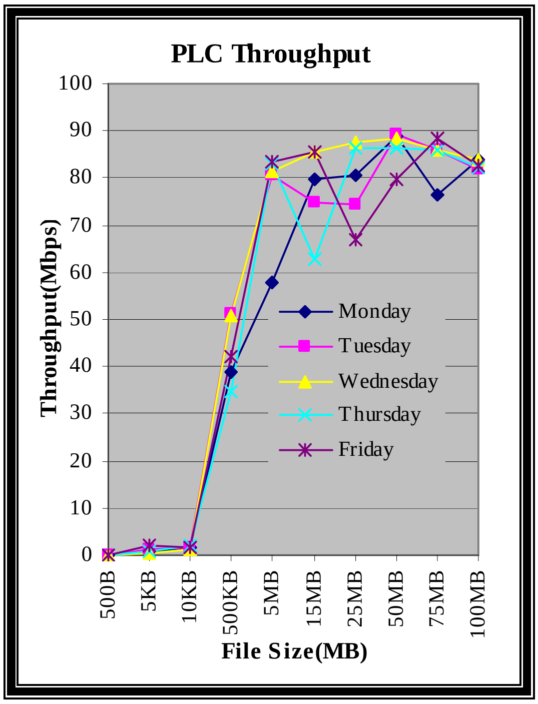

Figure 5.2: Broadband PLC Throughput.

The results recorded in Figure 5.1 above, (computed using equation (4.1) and (4.2)) shows a positive relationship between file size and time taken by the PLC node during file transfer. As the file size increases, transfer time also increases. From 500B to 5 MB file mark transfer time is below 1 second meaning that the smaller the file, the faster it is transferred. The reason which may be accounted to this is that at low file loads the PLC channel was not yet filled to its capacity and this meant less congestion for the PLC link.

This study found that as the size of the file to be transferred increases more time is needed to transfer it. Transfer time increased gradually but from 5MB file to 100MB as file size increased it took longer for the PLC node to transfer larger files. There is phenomenon on the 500B file in Figure 5.1 where transfer time is high and on other days it was low. This might be because by the time the request for data was issued by the client, it is possible that the data was already residing in the client's memory, and thus the request was satisfied immediately on Monday to Thursday than on Friday. This led to the 500B file having a lower transfer time on all other days except on Friday.

The study observed and found that as the file size increased, the longer it took for the PLC client to retrieve the files. The reason why broadband PLC took longer to transfer larger files might because of how our transfer script worked. The transfer script first reads the contents into the buffer, fetches the contents from the buffer and writes them to the disk. After writing to the disk the script verifies the whole data in the buffer to see is it has been written then it gives a success message. Verification is not part of writing to the disk but during disk writing, verification is considered but not yet done. Due to verification extra time is consumed. This might explain why the study found that at some instance throughput was far less than expected (high transfer time). Generally all the five transfer time curves from Monday to Friday are closely aligned and assumed a gradual increase or trend as the file size increases.

Figure 5.2 illustrates PLC throughput for each day from Monday to Friday. The study observed that from Monday to Friday files 500B, 5KB and 10KB files achieved throughput values of less than 10 Mbps. It is from the 10KB file that throughput ascends sharply achieving highest throughput value of 89 Mbps on the 50 MB file. Such a good performance can be attributed to the fact that the load on the grid was low during the time of the experiment and that only the machines involved in the test were allowed to run and all other computers or electrical gadgets were switched off. This lessened noise on the PLC channel. The other reason might be that it was in a laboratory environment meaning that PLC was operating at high frequency and the path was shorter and less attenuated leading to better performance. From the 5MB mark onwards all the curves except for the

Wednesday curve begin to have a peak and valley pattern more pronounced in some curves than in others. It is noticeable that, Thursday and Friday curves suffered rapid drops in throughput values on the 15MB and 25 MB file marks respectively.

One obvious observation from Figure 5.2 is that there are many severe throughput drops and variations with larger files .Standard deviation of 19.21783 Mbps and a variance of 57.50916 Mbps were observed, these were computed using the equations (4.3) and (4.4) respectively. This is so because when files are small, the link was less congested and throughput values had a small variance. In Figure 5.2 the curves experienced an almost similar trend with the Wednesday curve being a lot smoother. Peak throughputs were achieved at different levels and at different files marks as shown. We noticed that when PLC achieved its peak value it was accompanied by a gradual decline on throughput values as file size increased. From Figure 5.1 and Figure 5.2 it can safely be said that as offered load is increased, throughput grows until a saturation point. On reaching that saturation point throughput significantly declines as the file size is increased. Figure 5.3 and Figure 5.4 depicts the change in the average time and average throughput respectively.

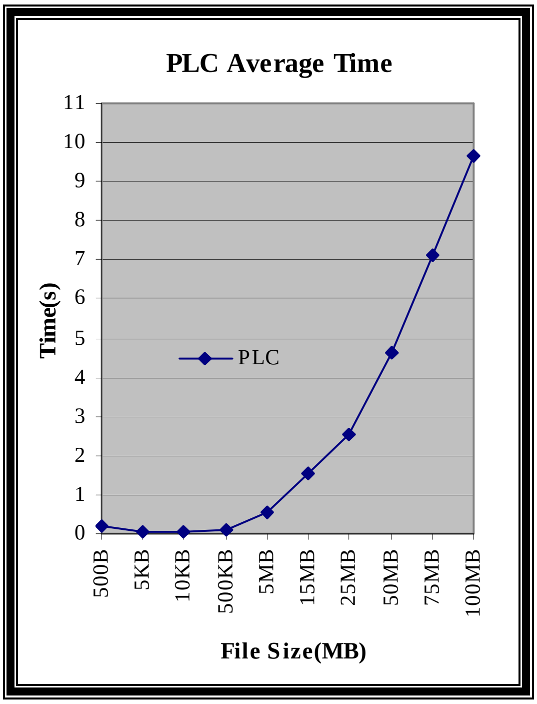

Figure 5.3: PLC Average Transfer Time

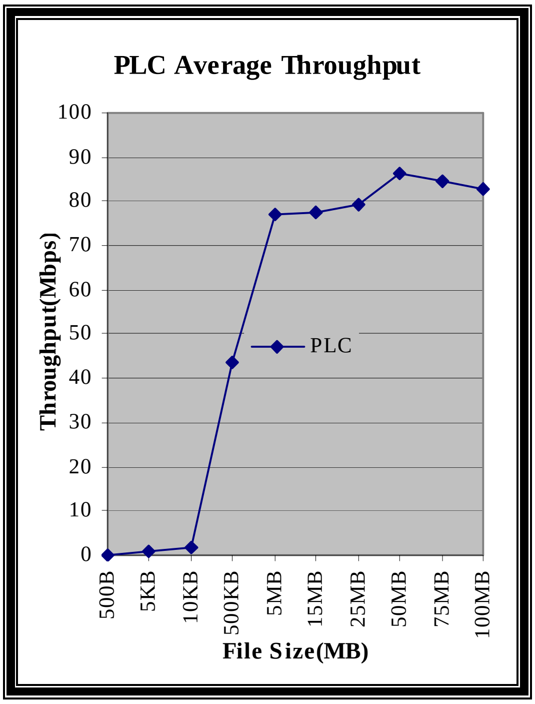

Figure 5.4: PLC Average Throughput

In Figure 5.3 a distinctive pattern is preset, there is a strong relation between the two variables: file size and average transfer time. Low transfer time for the first small files of below 1 second is observed. Then it increases gradually from 500KB till an average transfer time value of 9 seconds on the 100MB file. This confirms the results shown previously on Figure 5.1 that transfer time increases with file sizes meaning small files are retrieved faster than larger files. In other words different files of different sizes require different amounts of transfer time. The relation evident in Figure 5.3 between average time and file load variation may be confirmed by section 5.2 results.

Figure 5.4 clearly shows the average throughput for each file size and the maximum attainable throughput. The average throughput starts out low and it is below 10 Mbps for the first three files. A gradual increase in average throughput is observed peaking at 86 Mbps on the 50MB file and then it is followed by a gradual decrease till the 100MB file mark. The increase of the average throughput with file size from below 10 Mbps to an average throughput value of 86 Mbps may be attributed to the following reasons. Firstly it may be that during the time of experiment the characteristic impedance of Mistubishi PLC was greater than that of the LV grid leading to a high throughput value. Secondly it could have been because at low file loads the PLC pipe has not yet utilized all of its capacity. So, some of the bandwidth is still unused thus small loads mean low congestion. Therefore, PLC throughput increases as the file loads increases till it uses all of its available capacity from then on throughput values start to drop with file increase. In this case PLC is also dependant on the file load as it is with any other broadband technology as will be explained and confirmed in section 5.3.1.

A close analysis on Figure 5.4 shows that PLC equipment performance increased with the increase in file load up to peak throughput. PLC exhibits what seems to be a direct proportion between the file size and the PLC performance up to a certain point (86Mbps). Consequently, after 86 Mbps PLC performance reaches an unstable plateau while the transfer time continues increasing. The peak throughput is far less than the 200Mbps advertised for the PLC nodes in use. This suggests 1) a possible higher impedance mismatch at some point along the channel. This behavior is observed from the 50MB file mark onwards. This also suggests that 2) larger file loads transmission cause collisions with retransmissions of the packets leading to performance degradation. Figure 5.5 show the optimal load the PLC link can handle.

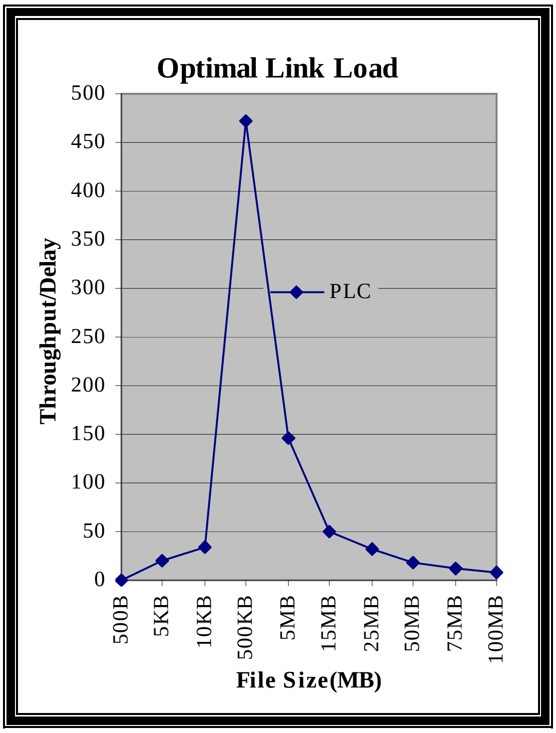

Figure 5. 5: PLC Link Optimal Load

Figure 5.5 above shows that the optimal load of the PLC link is around 500KB. This was computed from the experiment data, using the following relationship (5.1) expressing the power of a given network

$$\text{Power} = \frac{(\text{Throughput})^{\alpha}}{\text{Delay}} \tag{5.1}$$

Where α network factor is set to 1 in this case.

It should be noted that the results presented in Figure 5.3 and 5.4 are only reliable for an averaged performance indication. In this experiment scenario PLC shows the best throughput there is less contention and because the communication signal is less attenuated.

The performance of the PLC network increases more or less sharply up to the point where its effective copper bandwidth becomes insufficient for serving the increasing file load creating a huge, even unacceptable delay (Figure 5.2 and Figure 5.4). Conclusively laboratory experiments results depict that an increasing file load would have an increase on throughput till a point when a further increase would impose a negative effect on the PLC performance. All the file transmissions were successfully completed. The graphs illustrated in this section are actually a product of a series of observations and measurements recorded in a period spanning 5 days. Hence, it can be argued that inaccuracy of the transfer time and throughput measurements are low. The next section considers two nodes PLC and Ethernet LAN engaging in simultaneous file transfer connections.

5.3 Experiment Two: Laboratory Data Transfer in a Mixed Environment

This section presents, compares and analyzes results done in a mixed client laboratory setting with PLC and Ethernet LAN nodes. The results considered here were executed from Monday 17th to Friday 21st September 2007. The results are depicted in form of graphs showing how both nodes performed when subjected to the same file load and how they operated under the same conditions. The experiment configuration closely models a mix of nodes from different networks. Hence, in the following section the researcher expects the experiment to exhibit a different behavior.

5.3.1 Discussion of the PLC Data Transfer Multibuilding Experiments

Figures 5.6 and 5.7 show the transfer time results for both PLC and Ethernet LAN nodes respectively. Both figures have 5 curves depicting the transfer time taken by each file per day. Figure 5.6 shows that PLC transfer time on the 500B was higher than transfer time on Ethernet LAN (Figure 5.7). Both nodes took less than 1 second to transfer the first five files (500B to 5MB). It took less time to transfer small files than the larger ones a trend which was observed previously in section 5.2.1. The change in transfer time in Figure 5.6 is similar with minor variations to the change taken by Ethernet in Figure 5.7. Both graphs illustrate generally similar trend, less transfer time for smaller files then gradual increase as the file size increases.

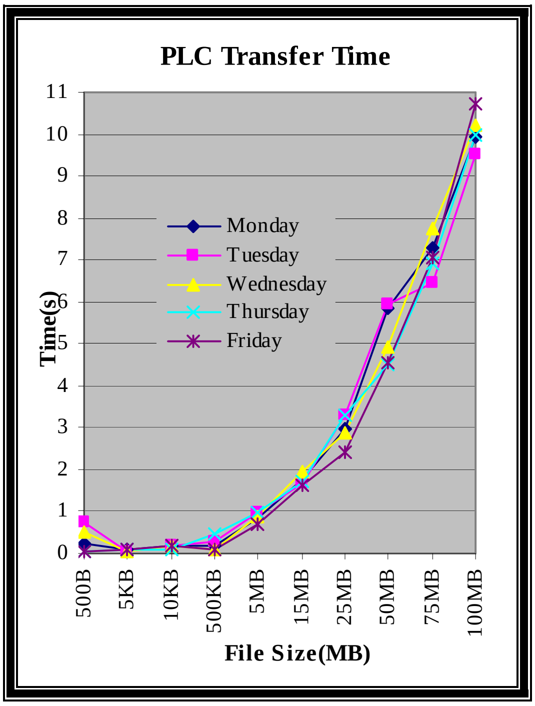

Figure 5.6: PLC Node Transfer Time

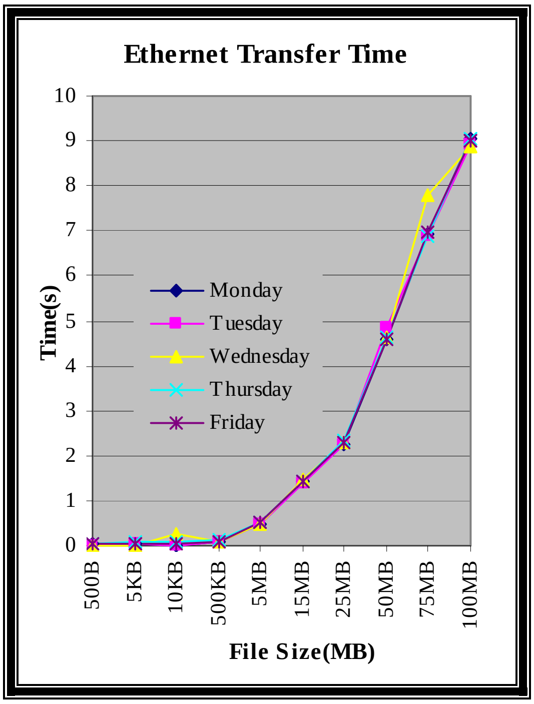

Figure 5.7: Ethernet Node Transfer Time

Figures 5.6 and 5.7 show that transfer time taken on 100MB file by PLC is more than that taken by the Ethernet LAN client on the same file. Such a high transfer time on PLC may have been caused by other processes running, packet loss or data corruption which triggered retransmission of some packets thereby adding extra time, hence more time was taken. Error-handling mechanisms are applied to PLC systems to solve the problem of transmission errors caused by LV disturbances. The application of forward error correction (FEC) and usage of Automatic Repeat reQuest (ARQ) mechanisms provides error correction and retransmission of defective data. However, this consumes PLC transmission capacity in form of overheads and introduces extra transmission delays. This might be another reason why PLC had such a high transfer time. This trend is also evidenced on the Ethernet LAN node. From research findings the study would like to safely argue that increasing the file size resulted in the increase of the transfer time on both PLC and Ethernet LAN nodes.

Figures 5.8 and 5.9 below illustrate the throughput achieved by PLC and Ethernet LAN. The throughput results were derived according to equation (4.1) where S_T reflects the size of the transferred file and T_T is the time between when the file was send and when the file was received. The graphs have 5 curves each curve depicting the throughput achieved for 5 days. On the first three files both PLC and Ethernet LAN throughputs are low. Though, throughput values achieved by PLC are lower than those by Ethernet LAN during that initial phase both nodes achieved throughput lower than 10 Mbps. From the 10KB file both nodes experienced a sharp rise in throughput until a certain point where throughput started to decrease.

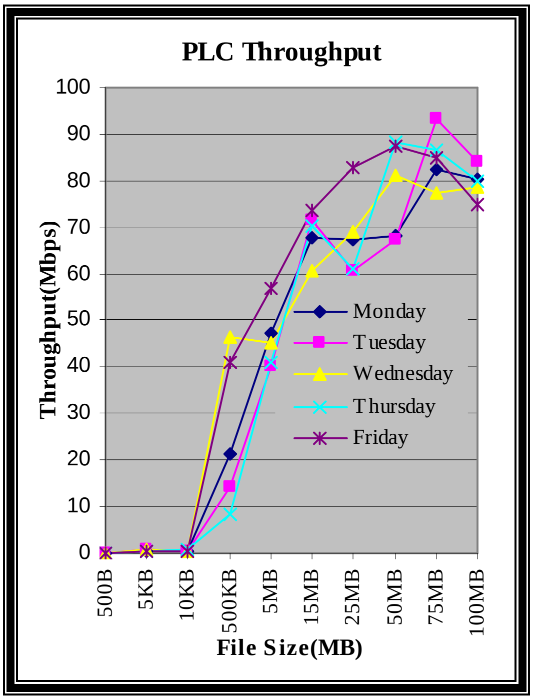

Figure 5.8: Broadband PLC Throughput

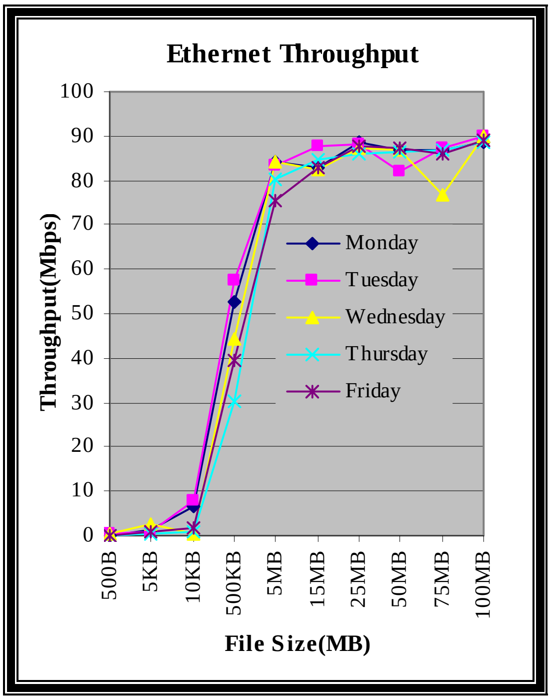

Figure 5.9: Ethernet Throughput

In Figure 5.8 there is a similar noticeable phenomenon on PLC throughput as was observed earlier on in Figure 5.2. There are valleys in throughput values starting from 15 MB with exception of the Friday curve. These valleys or drops are sudden and drastic depicting the deterioration of PLC performance. The fluctuation level from 5MB to 100MB is high, with a variance of 205.4647 Mbps computed using equation (4.4) and standard deviation of 14.33404 Mbps computed by equation (4.3) for PLC while Ethernet LAN variance and standard deviation is 12.42862 Mbps and 3.525424 Mbps respectively. The variance is generally very small up to network saturation when the files become larger.

A reason that may account for such drops, at this point, might be the unstable or variable nature of the PLC channel during the period of experimentation. Because the PLC channel is a shared medium switching on and off of computers, lights, electrical gadgets might have caused our throughput results to fluctuate. Another reason may be that those oscillations might have been caused by the competition for resources between PLC and Ethernet LAN. In Figure 5.8 and Figure 5.9 one can see that there is more than one incident where PLC and Ethernet LAN throughput was low. This finding could have been a result of the effect of processor scheduling on our measuring method or the transfer script. The researcher would like to argue that the reason for low throughputs can be attributed to the suspension of the measuring or transfer script by the processor because a process of higher priority needed to be executed and that added extra time to the transfer time leading to low throughput values.

In Figure 5.9 Ethernet LAN experienced less pronounced throughput drops. Initially Ethernet LAN throughput is low from 500B to 10KB and then it alters by rising steeply untill the 5 MB point from where it varies for larger files. Both Figures 5.8 and 5.9 exhibit similar patterns notably that throughput increases from a minimum of less than 10 Mbps to a high value then it starts to decrease. From the experiments, PLC node performed better on Tuesday than Ethernet LAN. PLC achieved highest throughput of 90 Mbps with Ethernet LAN achieving around 86 Mbps. The effect of the file size on throughput is interesting, especially when another node is added.

There are two important phases that can be identified in both Figures 5.8 and 5.9: a slow start and a saturation phase. In both Figures the slow phase starts at 500B and ends at 10KB. Also, PLC performance improved substantially from 10KB file point up to 75MB in the same way it improved with the Ethernet LAN. Throughput achieved by PLC is slightly lower than that achieved previously in section 5.2.1. This is so because it is affected by file load and by the addition of a competing Ethernet LAN node. But, when the file size increased, the observed data transfer time increased in a similar way it did in before section 5.2.1 experiments. The following Figures 5.10 and 5.11 present and compare average time and average throughput achieved by both nodes. Figure 5.10 graphs the average number of seconds the data had to take to transfer files over both networks. These calculated according to equation (4.1) and average values of different delays using equation (4.2).

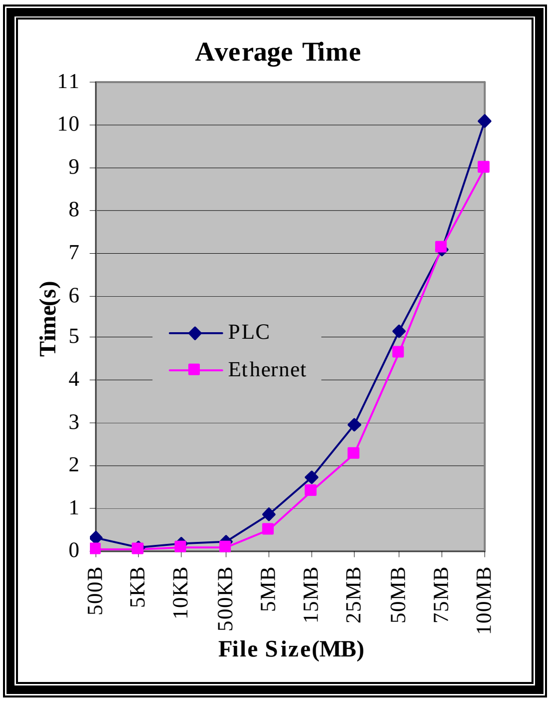

Figure 5.10: Broadband PLC and Ethernet Average Transfer Time

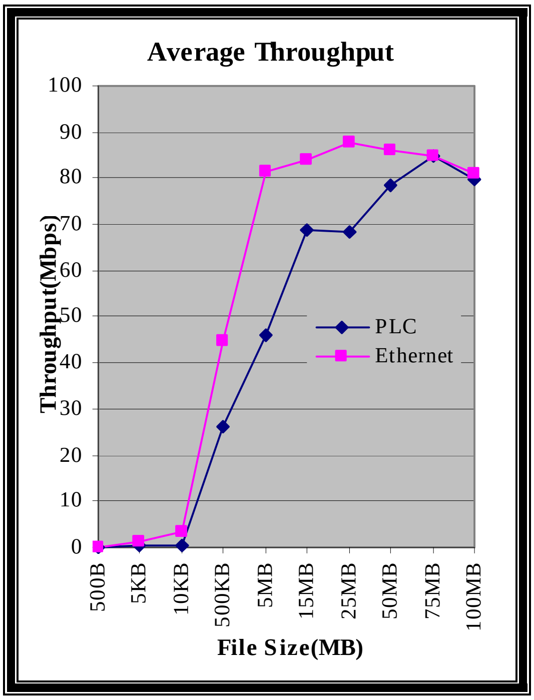

Figure 5.11: PLC and Ethernet Average Throughput

After a slow start phase, the average transfer time for PLC increases gradually identical to that of Ethernet LAN. In section 5.2.1 we observed a similar pattern. In transferring the 100MB file PLC ends by taking 10 seconds slightly longer than the average time taken by Ethernet LAN on the same file. But difference is not marked, leading to the understanding that PLC behavior is similar to that of Ethernet LAN. Hence, PLC has characteristics and capabilities equivalent to Ethernet LAN and any other broadband technology for that matter. As the file load increases, the average transfer time increases gradually for both nodes. On more than one occasion we observed that when using PLC the average time was slightly higher than when using Ethernet LAN. The overall PLC average transfer time is comparable to that achieved by Ethernet LAN. Generally PLC exhibited the same pattern and behavior to that taken by Ethernet LAN. This confirms that PLC has the potential and compares well and is capable of achieving better performance similar to that of Ethernet LAN.

Figure 5.11 shows average throughput and there is a modest reduction on throughput achieved by PLC. A rapid increase in throughput from the 10KB file point for both PLC and Ethernet LAN is observed. Ethernet LAN achieves its peak average throughput value of 87 Mbps while PLC achieves a peak value of 85 Mbps. There is no big difference. This shows that PLC compares well to Ethernet LAN though it surpassed PLC by a slight difference of 2 Mbps. Beyond the peak average throughput (85 Mbps), PLC limitations set in and the average throughput ceases to increase. It is worthy to highlight that PLC operates on the Carrier Sense Media Access/Collision Avoidance (CSMA/CA) communication protocol stack. It can be noticed that PLC throughput rise with increased file traffic and levels up to a point. At that point, collisions begin to occur with greater frequency, resulting in a gradual reduction in PLC network throughput. For both nodes one similarity can be noticed that average throughput increased rapidly and reached a maximum point and then decreased.

Ethernet LAN throughput drops with the file load increase but, the decline is more rapid for PLC than it is for Ethernet LAN. The Ethernet LAN node maintains a high average throughput level. On the contrary the PLC network maintains a slightly lower level of this parameter but with a similar pattern to that of Ethernet LAN. The Ethernet LAN node performed marginally better than PLC but overally both nodes yielded the best of throughputs values. Instead of gradual increase, sharp increases are observed for PLC, from 25MB file average throughput rapidly rises until it peaks and then sharply declines. For smaller files average throughput for both PLC and Ethernet is less than 10 Mbps. We encountered a similar pattern in section 5.2.1. As can be seen, from the peak value PLC average throughput starts dropping and same throughput deterioration is seen for Ethernet LAN starting after throughput saturation. Figure 5.12 shows the optimal link of both PLC and Ethernet LAN.

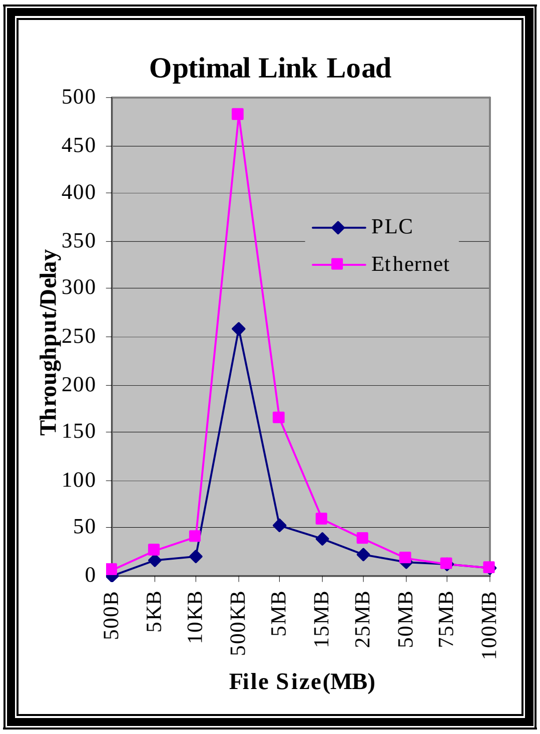

Figure 5.12: PLC and Ethernet Optimal Load

As indicated in Figure 5.12 above the optimal link load according to equation (5.1) for both PLC and Ethernet LAN is on the same file 500KB though that of PLC is lower than that of Ethernet LAN. By analysis the experiment results show that as file size increases throughput also increases untill a certain point, where further increase in file size leads to a decrease in throughput. Figure 5.8, Figure 5.9 and Figure 5.11 attests to this argument. The point from where throughput starts to decrease is different for both PLC and Ethernet LAN. All in all PLC performance is comparable to Ethernet LAN. As shown in Figure 5.12 both nodes share the same optimal link load file (500KB) and as such it confirms the comparability and capabilities of PLC as a broadband technology to Ethernet LAN.

The maximum PLC throughput obtained in section 5.2.1 is slightly better than that achieved under this section. In experiment one section 5.2.1 maximum throughput is achieved on the 50 MB while in this experiment it is achieved at the 75 MB file mark. In other words the throughput peak is achieved early in section 5.2.1. In this section it is achieved late and is lower in comparison to section 5.2.1 results. This confirms that addition of another node has effect and may lead to performance degradation thus throughput is dependent on the number of nodes in a configuration. PLC has shown to be dependent on the size of the file load and is affected by the number of nodes. Such a characteristic or behavior is bound to affect any broadband technology the same way it affected PLC and Ethernet LAN. All files were successfully transferred by both PLC and Ethernet LAN nodes during the experiments. Moreover PLC has proved that it has the potential to support broadband applications in a similar way Ethernet LAN does and this experiment attests and proves such an argument. This experiment has acted as a baseline for comparison and helped us compare PLC performance with other technologies such as Ethernet LAN.

5.4 Experiment Three: Multibuilding Data Transfer in a PLC Environment

Finally, we analyze and present how PLC performed in a multibuilding setting with an average distance of 80m between the master node in the Computer Science Laboratory (CSC) and the client node in the Geographical and Information Systems Laboratory (GIS). The researcher has executed these multibuilding experiments in the timeframe of Monday 22nd to Friday 26th October 2007. Section 5.4.1 shows all of the data transfer time and throughput results achieved by PLC during the experiment and gives detailed analysis of the results.

5.4.1 Discussion of the Multibuilding PLC Data Transfer Experiments

To investigate transfer time and throughput in terms of distance we had to put the client in remote location, the GIS laboratory and we kept the server in the CSC laboratory. The following Figures 5.13 and 5.14 show results for throughput and transfer time respectively as computed using equations (4.1) and (4.2). Before moving on to discussing the performance results, it is important to mention that results in section 5.2.1 and 5.3.1 will be compared to results presented here in order to deduce the influence of distance on PLC performance.

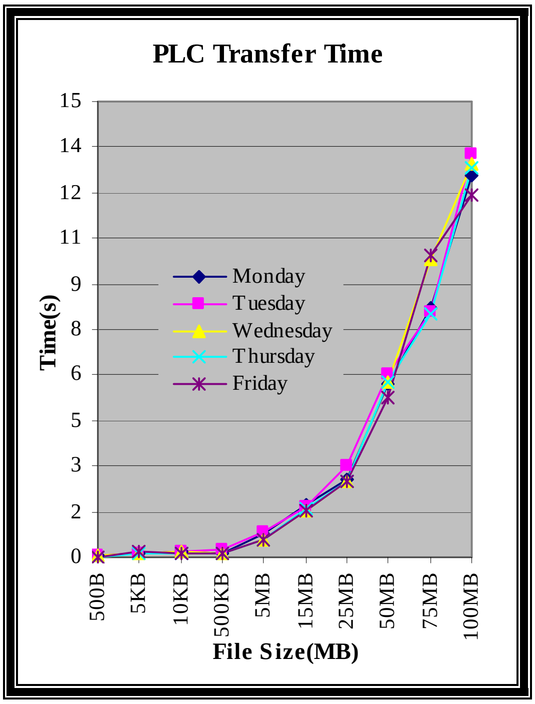

Figure 5.13: Broadband PLC Transfer Time

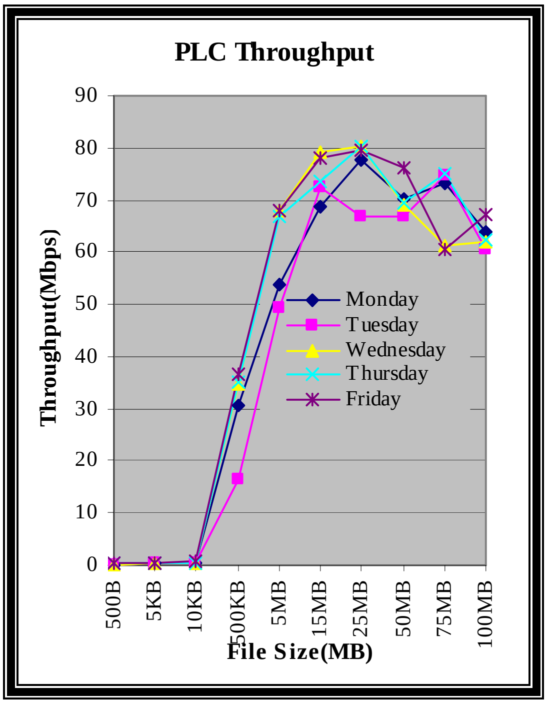

Figure 5.14: Broadband PLC Throughput

Figure 5.13 shows a gradual increase in transfer time as file size increases. From 500B to 5MB file mark the transfer time generally is below 1 second and from 15MB onwards transfer time rises rapidly going beyond 12 seconds except for the Friday curve. There was so much time taken retrieving files because the client was now at a more remote location (80m away) unlike when it was in the CSC laboratory. The transfer time in Figure 5.13 shows that an increase in distance leads to an increase in the transfer time. Such a delay among other reasons as will be explained later could have been triggered by other processes on the client machine that may have been consuming CPU resources at that moment of transfer. The results show that the further apart the CPEs are the longer it takes in order to make them communicate. This logically confirms that the higher the transfer time (because of distance) the lower the throughput is likely to be achieved. All in all PLC transfer time depicted in Figure 5.13 shows a rather steady and stable behavior on all 5 days of the experiment.

It can be clearly seen in Figure 5.14 that from 500B to 10KB throughput was below 10 Mbps. As the file size increased from 10KB throughput also increased for all the 5 days, achieving highest throughputs different points. Throughput started to fluctuate from 5MB file, achieving variance and standard deviation of 60.52959 Mbps and 7.780076 Mbps for the larger files respectively. Thus, the variance varied significantly, more with larger files than with smaller files. Because when retrieving the first three files the PLC network was not yet congested, thus the throughput is steady without much variance. In comparison to sections 5.2.1 and 5.3.1, Figure 5.14 shows that throughput decreases as the client moves away from the server and also that the larger the file the greater the performance degradation and variation.

As shown in Figure 5.13 and Figure 5.14 delay is high and throughput is lower than in the previous experiments (in section 5.2.1 and 5.3.1). This was so because great distances mean an increase in cable length this in turn increases attenuation of the communication signal, which logically decreases the throughput. As the length of the cable increases PLC become affected by multipath propagation because of numerous reflections caused by the joining of cables and their different impedances. This results in multipath signal propagation, with a frequency-selective fading. The most important effects influencing signal propagation are cable losses, losses due to reflections at branching points and mismatched endings of the cables. This might have caused the throughput to degrade as we moved the client further away to the GIS laboratory. Each day achieved its peak throughput value at different file points and at different throughput levels. As observed by the researcher and as shown in Figure 5.14 throughput decreased rapidly after reaching throughput peak.

As was the case in the previous configurations (sections 5.2.1 and 5.3.1) it can be seen that when PLC throughput reaches peak values, the PLC link gets saturated and throughput starts to decrease. There is performance deterioration for this experiment also as shown in Figure 5.14. PLC performed more or less in a way that any other broadband technology would have done in the same situation, an increase and then a decrease behavior in throughput as file size and distance increases. This so because PLC network utilization increased as the file load increased up to a certain point from where PLC could no longer sustain the file load, then throughput started decreasing. The results of the test indicate that throughput of the PLC network has dropped. The negative effect of file load and distance on PLC throughput is more compromised as compared to the previous experiments in section 5.2.1 and 5.3.1. The following Figures 5.15 and 5.16 show average transfer time and average throughput respectively.

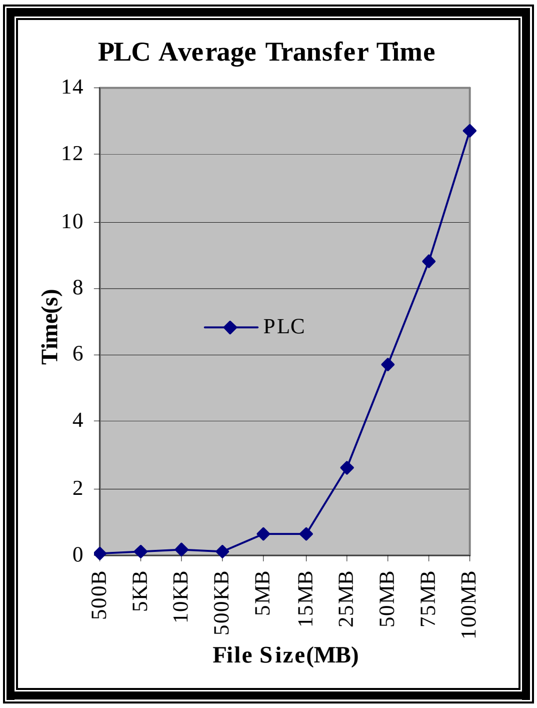

Figure 5.15: Broadband PLC Average Time

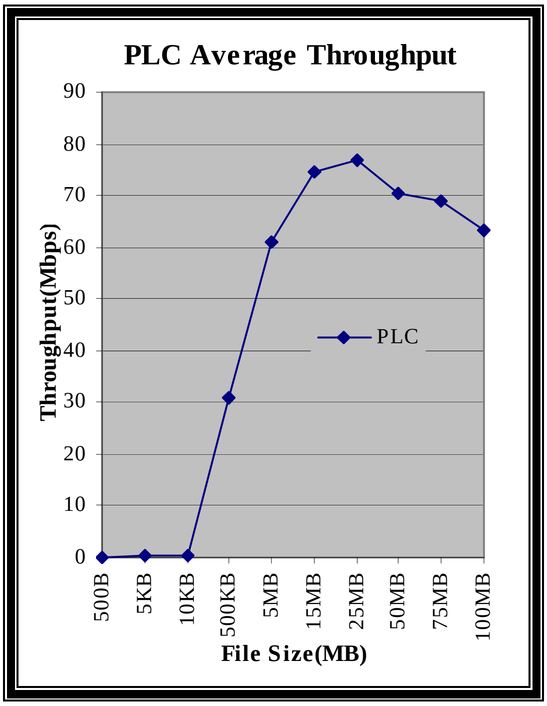

Figure 5.16: Broadband PLC Average Throughput

Similar to the transfer time pattern shown previously in Figure 5.13, average PLC transfer time show a slow start till 15MB file point then a considerable increase as file load increases. We noticed that as the file load and distance increases, PLC start to take longer transfer time consequently decreasing throughput. Because distance has increased and that at high file traffic loads, data collisions, cyclic redundancy checks and retransmissions were more prevalent it diminished PLC performance dramatically. As depicted in Figure 5.15 it is possible that collisions were so frequent that when transferring larger files such as 100MB transfer time went up to over 12 seconds.

Figure 5.16 shows PLC throughput rising first lowly from 500B to 10KB, then rapidly until the network is fully utilized achieving a maximum average throughput of 76 Mbps. At that point, throughput saturates. With contention-based networks like PLC (CSMA/CA), the fall-off after a certain point is fairly rapid because collisions interfere with virtually all traffic on the network thus reducing the performance. The amount of performance degradation in PLC performance in Figure 5.16 is considerable as compared to PLC performance in the previous experiments (sections 5.2.1 and 5.3.1). Changing file size improves PLC performance untill a point where increasing file size further decreases performance (with increasing average transfer time). Figure 5.17 below shows that the optimal load of the PLC link is around 500KB as computed using equation (5.1).

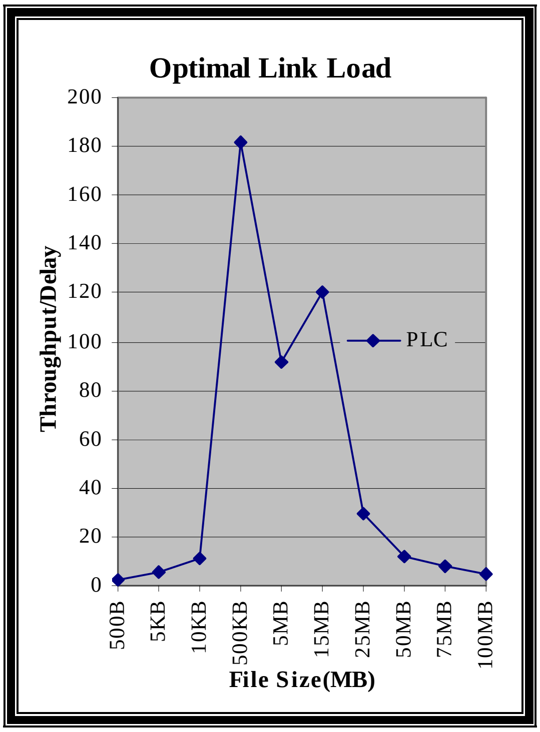

Figure 5.17: Broadband PLC Optimal Load

By observing Figure 5.14 and 5.16, it is not difficult to conclude that there is a relationship between throughput and distance. This is confirmed by the high throughput values exhibited in section 5.2.1 and declining throughput values depicted here in Figures 5.14 and 5.16. In Figures 5.13 and Figure 5.15 there is a positive relationship between transfer time and distance. PLC had relatively high transfer time (leading to lower throughputs) as compared to values achieved previously in 5.2.1 and 5.3.1. It can be noted that increasing distance leads to an increase in transfer time and after a certain point throughput decreases. The main conclusion from this set of experiment is that at low loads the throughput increases as the file increases up to a point where a high file size imposes a drop in performance gradually because of distance. PLC throughput dropped with distance in the same way it does with any other broadband network. It was observed that broadband PLC has performance behavior similarities and qualities as those possessed by broadband technologies such as Ethernet LAN. In addition broadband PLC was able to transfer and maintain good performance over the entire CSC and GIS grid.

However, distance affected PLC performance when compared to laboratory experiments results presented in sections 5.2.1 and 5.3.1. The multi-building experiments results have shown that distance compromises performance. As file load continued to grow and the distance between increased throughput was affected negatively. A reason for this, apart from reasons given before, might be low signal power PLC is allowed to operate at. Broadband PLC can act as an antenna thus becoming a noise source for other communication systems working in the same frequency range. So, broadband PLC has to operate with a limited signal power, this in turn decreases its performance with distance. As a result, of limited signal power PLC become more sensitive to disturbances on the grid and longer distances (CSC to GIS) this consequently, decreases its performance. It is also good to point out that during the experiments broadband PLC was able to transfer all the files across the distance. PLC exhibited full connectivity since all nodes were visible all the time of the experimentation even after we increased distance. In all the experiments executed, the research findings revealed and proved that PLC has future and potential to handle and support broadband applications as efficiently and effectively as Ethernet LAN.

5.5 Conclusion

The chapter has presented broadband PLC performance under three real world experiment configurations. The chapter enumerated extensively each experiment. Comprehensive description and analysis of transfer time and throughput results was presented. These results were shown, explained and compared in 17 conclusive graphs. The research explained poor and best PLC performance as a promising broadband communication technology. Furthermore the chapter analyzed and discussed PLC performance in comparison with Ethernet LAN. The results have shown that broadband PLC performance is similar with minor variations, to that of the known broadband technologies such as Ethernet LAN. Thus, the real broadband PLC network was observed to provide throughput stable and comparable to Ethernet LAN with full connectivity. This confirms and shows the potential of PLC as a technology capable of data communication over residential and office grids. In the next chapter we summarize our contributions, present our conclusions and discuss possibilities for future research work.

Chapter Six

Conclusions and Future Research

This chapter presents a discussion of the deliverables of the research in parallel with the research objectives that were presented in the first chapter. Stating the extent to which the research statement has been fulfilled by providing the main achievements and conclusions of the research. A rundown of the thesis is presented and a comprehensive summary of the important results of the research is offered. In addition, it concludes by describing potential subjects of interest for future research that could be extended and done in this area of research.

6.1 Research Discussion and Goals Achieved

The research goals provide the structure of this section, each research objective as stated in Chapter 1 is recalled, answered and discussed accordingly. As whole, the research done and discussed in this thesis answers the research topic: "*The Development of Methodologies for Deploying and Implementing Local & Medium Area Broadband Power Line in Residential and Office Electric Grids*". All the six chapters of this thesis explain in detail how the research was undertaken in providing comprehensive analysis and deductions to the research problem. The research findings have achieved research goals and made contributions to the existing volumes of knowledge on broadband PLC research by providing and elaborating comprehensive conclusions and contributions to the problem of the statement defined in Chapter 1. The research goals, outlined in section 1.3, are revisited and followed in the same order according to the full scope of this research. Addressing the individual research goals, conclusions can be made for each one:

First objective of the research:

- *Developing methodologies for deploying broadband PLC in residential and office settings acknowledging reliability and redundancy given the noise level on PLC.*

The research came up with methodologies for successful PLC deployment in residential and office areas. The research proposed possible methodologies that can be developed for typical MV and LV PLC networks. The designing of PLC methodologies has demonstrated to require special knowledge about the internal PLC equipment functionality and implementation. The research evaluated the design requirements and description of the PLC communication equipments. This study then proposed MV, LV broadband PLC architecture and LV user requirement methodologies in chapter 3. In this sense, the research findings explained advantages and disadvantages of each proposed broadband PLC methodology. The proposed and presented broadband MV and LV PLC methodologies encompass both residential and office electric grids. These PLC methodologies provide reliability, efficiency and considerable throughputs (as will be attested by the second objective) to meet requirements of broadband applications in residential and office electric grids.

Second objective of the research:

- *To execute exhaustive experiments on broadband PLC in three environments which closely mirror residential and office settings.*

Through experiments in Chapter 4 the research has proven that broadband PLC can achieve significant throughput and that it is comparable to other existing broadband technologies in particular Ethernet LAN. As indicated by the results in chapter 5, device arrangement affects significantly the achievable throughput. The research analyzed broadband PLC performance in three different experimental configurations designed in laboratory and multibuilding LV settings. In *Experiment One: Laboratory Data Transfer in a PLC Environment* PLC achieved 86 Mbps. This is considerably adequate throughput to meet requirements of most broadband applications. This research did show that at present such throughputs are already sufficient for many useful innovative broadband applications, since a number of useful services are already feasible with data transmission in the kbps range. Furthermore, Mistubishi PLC speeds are of the order of 200 Mbps and higher speeds are envisaged within a number of years.

In comparison to Ethernet LAN broadband PLC achieved 84 Mbps in *Experiment Two: Laboratory Data Transfer in a Mixed Environment* while Ethernet achieved 87 Mbps. These results show that broadband PLC has the capacity to accommodate file load services [Tinarwo *et al* 07] and is able to handle application data transmission just like Ethernet LAN. Furthermore the results demonstrated that PLC cohabitated and shared data with other networks in this case Ethernet LAN without problems or irregularities. In *Experiment Three: Multibuilding Data Transfer in a PLC Environment* broadband PLC achieved 79 Mbps and all files were transferred with full connectivity over the entire distance of 80 m between Computer Science Laboratory (CSC) and the GIS Laboratory. It was able to maintain good performance over the LV grid distance. Though, it was observed that PLC throughput dropped with distance the research argued that PLC behaves like any other broadband technology and it has qualities as those possessed by broadband technologies such as Ethernet LAN. According to the measurements and analysis undertaken the research advocates PLC as a broadband infrastructure for homes and offices based on the fact that it was able to transfer and support communication among nodes in all the experiment configurations. The research has shown that PLC can provide broadband applications such as file transfer with adequate quality of service. The delivery of small to large files was successful in all the experiments undertaken. PLC demonstrated performance similar to that observed in Ethernet LAN. The only major difference is that PLC is still a maturing technology [Hrasnica *et al* 04] with more research and technological advancement it will become fully developed.

During the experimentation period there was no phenomenon observed that was contrary to the results and conclusions observed and drawn by this research. To that end, the research project has been successful in showing the potential of broadband PLC, as a promising future broadband technology that can also be utilized in efforts to combat digital divide, while also providing a framework in which broadband PLC research can be done to make it a reality. Arguing and deriving from the results in Chapter 5, and by observing PLC experimental deployments in Chapter 4, it can be concluded that the research have shown that broadband PLC can perform remarkably and considerably well and is equivalent to other broadband technology existing on the market. This research has also revealed that broadband PLC technology presents a cost-effective alternative for deploying broadband networks. Nevertheless, it is worthy to highlight that, electrical supply networks were not designed for communications; therefore, they do not represent a favorable transmission medium.

Third objective of the research:

- *To undertake a comprehensive presentation of broadband PLC case studies literature and a detailed analysis of deployments currently being undertaken in the broadband PLC research area.*

Research and developments in broadband PLC are relatively new and relevant information is still very scattered and not easily available for research purposes. Lack of collective information had been one of the primary motivations behind this research. Commercial providers hold most of the available data concerning the locations where broadband PLC is commercially available and actually being tested. These organisations have elected not to make that data available on the public research domain. This research has managed to gather and evaluate literature on broadband PLC trials and commercial deployments. It serves as a general reference on PLC case studies literature with the presentation of a comprehensive and detailed analysis of deployments inside and outside of South Africa. Broadband PLC has proven that, it is a viable broadband technology as reviewed and indicated in detail in Chapter 2. In addition, the research has shown that broadband PLC has grown tremendously as a technology from first experiences to large-scale technological trials and commercial roll-outs [Little04]. Currently, there are on-going PLC experiences in South Africa [Kuun06], [Naidoo07] and commercial deployments in different countries. The promising results of these broadband PLC experiences validate the technological viability and potential of medium and local area PLC as a technology for broadband delivery in residential and office grids.

6.2 Future Research Work

Future research can entail measurements and comparisons of results of PLC deployed in a hybrid network with wireless or other networking technologies. And analyze their influence on each other by involving significantly more users, wider area and deduce on the basis of the network formed and tested at various major practical locations. This research did not experiment on the performance of delay sensitive traffic, combined delay sensitive traffic and elastic data traffic. Although, the study could not explore the QoS service and packet priority provided by the real PLC network it will be interesting to research that as an extension and also the effect of mixed traffic on a PLC network. However, for PLC to fully exploit its potential a clear and technology neutral regulatory framework for PLC is needed. Despite the fact that, active work in PLC regulation has allowed for commercial PLC deployments to be a reality, special attention must be paid to the evolution of regulation and standards [Little02], so that investments in PLC networks today are guaranteed in the future.

6.3 Overall Conclusion

The activities of the research have been of great interest and would be of great interest to broadband PLC research community. The research results have provided important information about PLC methodologies and end-user application performance when running in a PLC environment. These experiments have provided information about the performance and robustness of the broadband PLC infrastructure and in comparison with the Ethernet LAN infrastructure under low, intermediate and high file load. The research may help with the introduction of advanced ftp-oriented techniques and differentiated broadband services. In addition, this research is important in that it has contributed an independent study of ftp workload throughput over possible broadband PLC methodology types and three experimental configurations were deployed to establish broadband PLC data transfer performance.

This study also identified a number of current constraints and future conditions that will be required to facilitate and encourage large-scale adoption and application of PLC. With sound infrastructure planning and innovative regulation, PLC has the potential to provide high-end services at lower cost [ITU03]. Currently, there are several bodies that try to lead the way for standardization of broadband PLC networks. These bodies are international organizations and they are a valuable input in the on-going broadband PLC standardization activities, bodies such as PLCforum (PLCforum), HomePlug Powerline Alliance (HomePlug) and Open PLC European Research Alliance (OPERA) [Campi *et al* 05]. Broadband PLC standardization activities are also included in the works of European Telecommunications Standards Institute (ETSI) and European Committee for Electrotechnical Standardization (CENELEC) [Little04] among others.

In South Africa ICASA/STANSA has mandated a workgroup in 2002 for policy and regulations on PLC [Naidoo07]. The workgroup combines the expertise of ICASA, STANSA and industry stakeholders for the benefit of the ICT industry. The workgroup also works closely with international organizations mentioned in the previous paragraph. The workgroup has obtained permission from STANSA to conduct tests and develop technical specifications on PLC equipment. However, further work should be performed in order to achieve a standardized PLC technology with improved features and behavior [Hrasnica *et al* 04].

It must be made clear that this study did not argue that PLC is the mother of all broadband technologies. In fact, the research is advocating for PLC potential to be given time as was the case with other broadband technologies. History on broadband technologies tells us that technology evolve because of constructive criticisms. At the moment, PLC is going through growth phases as did other broadband technologies, so much research is still needed to support it. As mentioned earlier, the study is not arguing that PLC is an all embracing technology and that alone it will bridge digital divide. Rather, this research argued for the integration and participation of PLC as a solution to digital divide and broadband delivery. In this regard, PLC does not stand as the only last-mile technology, but it appears to emerge as an integrative significant broadband solution. Depending on the regional or national situation, and due to varying demands and capabilities, it is likely that the overall information society infrastructure will have a hybrid network infrastructure. As a result, MV and LV broadband PLC methodologies (or networks) are certainly positioned as a good complement or alternative for broadband delivery, since they can provide a permanent, two-way connection to local and medium area residential and office electric grids as analyzed and presented by this research.

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