DISSERTATION TITLE

Power Line Telecommunications Option in Rural KwaZulu-Natal

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Declaration

I, Thembinkosi Emmanuel Mhlongo, Student Number 9801328, hereby declare that the dissertation entitled **Power Line Telecommunications Option in Rural KwaZulu-Natal** is a result of my own investigation and research, and presents my own work unless specifically referenced in the text. This work has not been submitted in part or in full for any other degree or to any other University.

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Abstract

Power Line Communications (PLC) is a recent and rapidly evolving technology, aiming at the utilization of the electricity power lines for the transmission of data. PLC technology opens up new opportunities for the mass provision of local, last-mile access at a reasonable cost. PLC can furthermore provide a multitude of new Information Society services – both in the energy and telecom domains - to residential and commercial users that are difficult or costly to implement through other technologies.

PLC technology has a number of important strengths: it offers a permanent on-line connection as well as symmetric, two-way communication; it has good performance, very good geographical coverage, and is relatively cheap because most of the infrastructure is already in place. Currently, the main weaknesses of PLC technology are that it is still in the developmental stage.

It is likely not to be the only one: rather, it will be part of a range of complementary technologies, because each technology yields a different compromise between bandwidth, reach, noise immunity, and cost. This report starts by looking at access technologies and describing the power line as a communication medium and then frequency response and noise characteristics. A transmission technique (OFDM) that avoids power line noise and uses the common modulation formats is also explained.

The results of this work shows that the power line technology can be used as a communication channel for urban areas and fast developing rural areas. This is because of the bandwidth is uses. A proposed future research for slow developing rural areas is found in the conclusion.

TABLE OF CONTENT

List of Abbreviations

AC	Alternating Current
ACF	Autocorrelation Function
ADSL	Asynchronous Digital Subscriber Line
APSK	Amplitude and Phase Shift Keying
ASK	Amplitude Shift Keying
ATM	Asynchronous Transfer Mode
AWGN	Additive White Gaussian Noise
bd	baud
BER	Bit Error Rate
BICM	Bit Interleaved Coded Modulation
BPL	Broadband Power Line
BPSK	Binary Phase Shift Keying
BRI	Basic Rate Interface
CENELEC	European Committee for Electrotechnical Standardisation
CSED	Channel Symbol Expansion Diversity
CSI	Channel State Information
DAPSK	Differential Amplitude and Phase Shift Keying
dB	Decibel
DECT	Digital European Cordless Telephone
DFT	Discreet Fourier Transform
DOCSIS / EuroDOCSIS / DVB Euro-modem	European Cable Certificates
DQPSK	Differential Quadrature Phase Shift Keying
DSL	Digital Subscriber Line
DSLAM	Digital Subscriber Line Access Multiplexer
DVB	Digital Video Broadcasting
EnBW	Energie Baden-Wurttemberg

ESCOM	Electricity Supply Commission
FCC	Federal Communication Commission
FFT	Fast Fourier Transform
GMSK	Gaussian Minimum Shift Keying
GSM	Global System for Mobile Communication
HDSL	High Bit Rate Digital Subscriber Line
HF	High Frequency
HV	High Voltage
ICI	Interchannel Interference
ICT	Information Communication Technology
IF	Intermediate Frequency
IP	Internet Protocol
ISDN	Integrated Services Digital Network
ISI	Intersymbol Interference
kbps	kilobits per second
kHz	kilo-Hertz
LAN	Local Area Network
LVEDN	Low Voltage Electricity Distribution Network
MAN	Medium Area Network
MB	Megabytes
Mbps	Mega bit per second
MHz	Mega-Hertz
MLC	Multilevel Coding
MSD	Multistage Decoding
OFDM	Orthogonal Frequency Division Multiplexing
PDF	Probability Density Function
PLC	Power Line Communication
PLCS	Power Line Carrier System
PLL	Phase Locked Loop
PLT	Power Line Technology
PSK	Phase Shift Keying

PSTN	Public Switched Telephone Network
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RADSL	Rate Adaptive Digital Subscriber Line
RF	Radio Frequency
SCADA	Supervisory Control and Data Acquisition
SDSL	Symmetrical Digital Subscriber Line
SNR	Signal-to-Noise-Ratio
TETRA	Terrestrial Trunked Radio
VDSL	Very High Bit Rate Digital Subscriber Line
VSAT/Satellite	Very Small Aperture Terminal/Satellite
WAN	Wide Area Network
WCDMA	Wideband Code Division Multiple Access
WLL	Wireless Line

List of Figures and Tables

CHAPTER ONE

INTRODUCTION

1.1 RURAL TELECOMMUNICATION

"Economic development in Africa will depend heavily on the development of the information sector. Countries will need the ability to communicate efficiently with local and overseas markets. Many of the development problems facing African countries have scientific and technological components that will require solutions to be developed in Africa by African scientist, however lack of information is still a critical constraint" [2]. In rural areas, the sparse and scattered population pattern typically translates into high costs to the carriers providing local and long distances services. Both state regulatory commissions and the Federal Communications Commission have always said that affordable telephone services must be available throughout each state – in the rural as well as urban areas. But in the midst of the regulatory change, how can we be sure that rural subscribers will actually receive affordable phone services? [66]

The rural sectors of the Third World and, to a certain extent, newly industrialized countries, are often subsistence economies whose primary function is to provide labour to a more advanced and usually urbanised sector. These rural sectors are usually characterised by the basic lack of clean and adequate supplies of water, food, fuel, shelter, roads and power. It is difficult therefore to even attempt to prioritize telecommunication development in rural areas until these basic need have been satisfied. Rural telecommunication is an issue of concern because statistics shows that, most of the populations in developing countries live in the rural and often isolated areas; therefore the majority of the population in these countries do not have a ready access to a telecommunication infrastructure. The facts show that, 12 % of the world's population resides in Africa with a tele-density ratio of 1.74 %. There are more phone lines in New York or Tokyo than there are in the whole of Africa [2].

The provision of the various services in an urban area is usually not a very big problem since a number of options are available ranging from wireless technology, LAN/MAN/WAN, wireline networks, optical fibre cabling and VSAT. Recently many authors have studied the technology viable for communication in non-urban areas and low density in different environment especially in developing countries, by reflecting the already available wireless technology adopted in some of urban areas of developing countries. These wireless technologies are Cellular networks (GSM and WCDMA), VSAT, Microwave based wireless access, TETRA (Terrestrial Trunked Radio), Cordless (CT2, PHS, Digital European Cordless Telephone (DECT), Integrated/Combined VSAT/WLL, Integrated/ Combined Microwave/WLL and proprietary Solution (e.g. DaRT). All these technology differ in their basic capacity and coverage design. Some of the technologies, which have realized to be the candidates for communications in such areas, are VSAT/Satellite systems. But according to the indications in various developing countries the project implemented using such communication media have either failed to be implemented or those which have been implemented failed to satisfy the requirement of communication in such areas [1]. The reasons behind this include the cost of infrastructure of the proposed technology due to the few potential end users, hence causing the failure of communication in non-urban and low-density areas in developing countries.

The role of telecommunications in transmitting information can be particularly significant in rural areas where alternative means of obtaining and conveying information such as personal contact, transport, medical care and postal services are likely to be less accessible. Thus, it is a fact that in Africa where population and economic activities remains largely rural-based, sharing information is vital if Africans are to contribute to finding the solutions to their own development problems.

Power line network is of basic consideration because the potential telecommunication end users first consider having electricity in their household and business areas or tend to implement the network from electrical power grid or private operators network. It has been observed that in South Africa about 35.6 % of residences in rural areas and 67 % in urban areas have managed to have electricity, while the average telephone tele-density stands at 10,05 per hundred inhabitants. It has also been observed that the percentage of the households with telephone in rural areas is 4.7 % as compared to 45.7 % in urban areas [5] (see Figure 1.1).

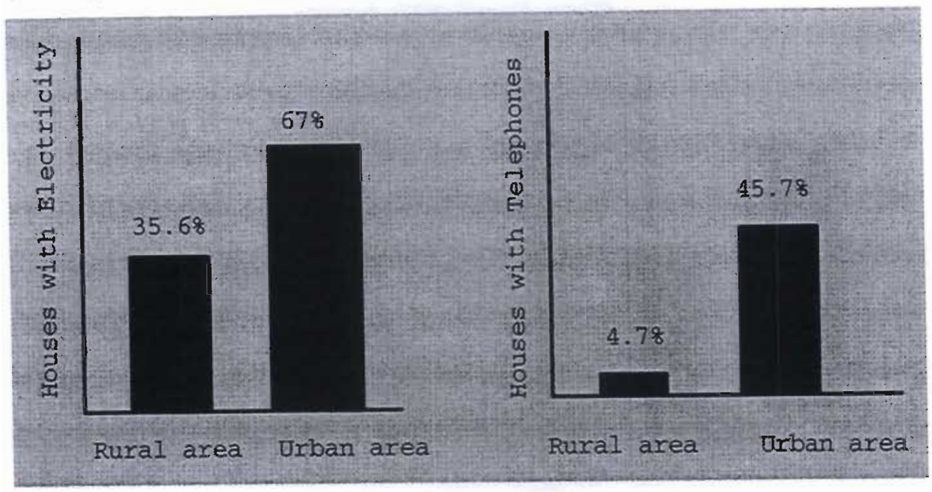

Figure 1.1: Penetration of power lines and telephones in South African households

This is largely due to the distance between neighbours in rural areas and also the cost of new infrastructure. If these figures are compared to that of the households with electricity, it can be seen that if power lines are used as a communication channel, means of communications will be at most people's disposal.

Researchers have already investigated the applicability of Power Line Network for communication in developed countries and already the possibilities of communication in such medium have been realized. The power line networks have proved to have enough bandwidth for communication at any data rate [1, 8 -10].

The limitation which is still hindering communications through this medium is the regulations by communication authorities in various countries; for example in Europe, CENELEC (European Committee for Electrotechnical Standardisation) standard have regulated the operation frequencies and maximum power to be transmitted in PLC environment [1]. The same applies to USA and Japan but differently from Europe, the

Japan and USA PLC both frequencies and power operations are differently and also only frequencies have been regulated basing on radio operations frequencies. These have caused researchers to review the operations in PLC. The frequency band and maximum power to be operated is still under research in various countries, because PLC radiates like antenna and can cause interference to other communication medium if it operates under same frequency with for example wireless, normal broadcast radio and so on.

1.2 THE POWER LINE NETWORK

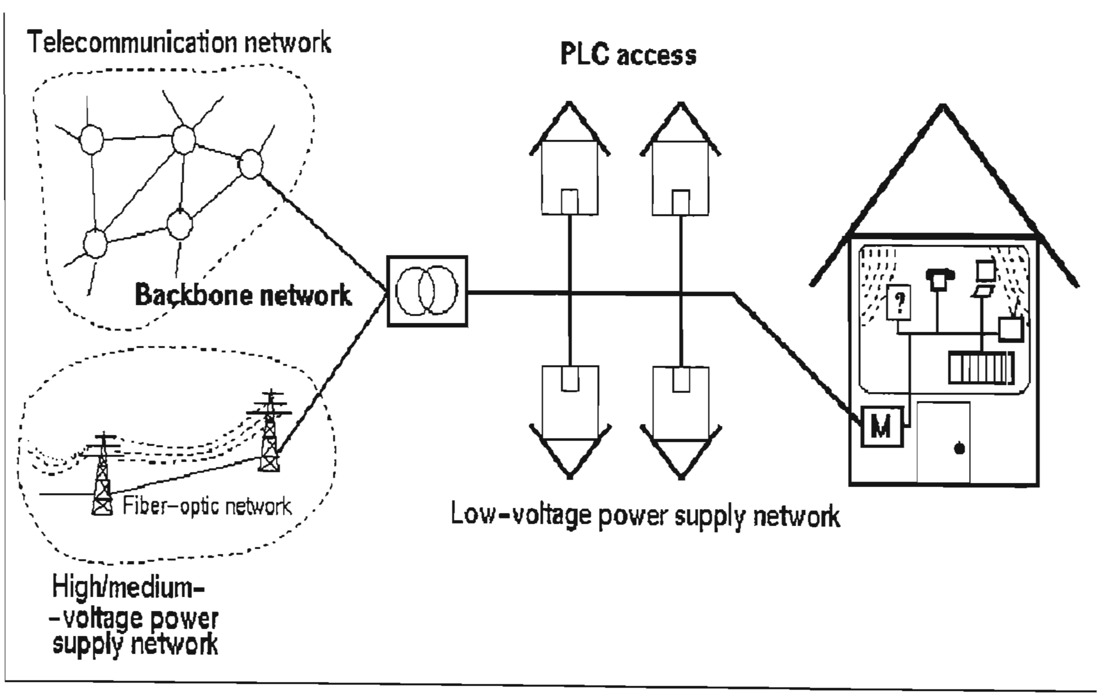

Figure 1.2: PLC access network (Source: Intellon Corp [17])

The power line networks implemented in different countries have shown to have similarities. A typical PLC access network is shown in Figure 1.2. In Europe for example from households to distribution transformers the maximum distance is 500 meters and in Africa it extends up to 1.2 km to distribution transformer and up to 5.2 km to primary substation [4]. This, in PLC environment, is the called last mile. PLC in principle is affected by noise, but this has shown to be similar with other communication channels like cellular and radio, this limits the performance to be achieved. In developing countries the telecommunication regulators have not yet considered PLC as a transmission medium and nothing has been done to regulate it for communications. But still various companies are operating locally. For example in Tanzania, Tanzania Electrical Supply Company (TANESCO) is communicating in power line network high-tension grid basing on CENELEC standard due to manufacturer of the equipment. Many researchers have already pointed out that IP based network is the cost effective solution for communicating towards non –urban and low density areas and technologies in consideration include satellite [1]. The reasons behind this are that data networking equipment is easily available at competitive prices, all links integrates data and voice packets on per link basis, enabling higher channel utilizations and packets are acceptable even when network is busy [1], [4]. In addition, in developing countries the power line network is well established and where the network is not available can be implemented because the electricity has been shown to be the basic requirement for development. In KwaZulu – Natal, this can connect up to 175 house holds in non-urban areas per mini sub-transformer. In addition, this type of technology will make more customers to opt for communication because the network will be at their disposal. Hence having many customers and cost effective technology of IP, and also the power line network which has not only been implemented purposely for communication but for providing electricity will enhance the operators to invest and also to make profits.

1.3 WHY POWER LINES FOR COMMUNICATION

The companies that provide Internet services have not been carrying on as usual. They realize that users of the Internet are hungry for faster service than phone lines and 56k modems currently provide. Additionally, many Internet service companies seek to increase their profitability by offering Internet access, local phone calls, cable TV, and perhaps long distance phone services to their customers in one relatively inexpensive package. The solution is a high bandwidth network with links to each customer's location.

Implementing this type of network has not proven to be easy and not accessible and affordable to rural population.

Telephone companies have offered high bandwidth lines for many years. For the most part, the cost of these lines and the equipment needed to access them has limited their usefulness to large businesses and remote areas. The lone exception has been Integrated Services Digital Network (ISDN) that has won over some residential customers. ISDN offers fast Internet access (128k) at a relatively low cost. Telephone companies have begun to replace the phone lines that connect residences and business to the standard telephone network with higher bandwidth lines. However, this process is costly and time consuming. Such higher bandwidth networks will not be operational for several years to come.

Cable television companies have also jumped into the Internet access market. The lines that carry cable television are much faster than standard phone lines or even ISDN. The major problem with cable TV's attempts at providing Internet access has been the unidirectional character of cable TV lines. Cable TV lines are only designed to bring information to the customer, not to get input from the customer. This fundamental flaw in cable TV lines has increased the costs of developing Internet access services based on them. Thus, most cable TV Internet access systems will not be ready for several years in many countries.

Wireless solutions have also been proposed, but have run into problems. First, the performance and reliability of wireless solutions has not been up to the level of any of the wire line solutions described so far. Second, the ability to send data from a customer to the Internet requires much more equipment than simply receiving data. This additional equipment makes wireless Internet access much more expensive than cable TV [6].

None of the available Internet access services offer the right balance of cost, convenience, and speed. Power line communication technology, also known as PLC, could change all that. It promises customers high speed Internet access through electrical networks. Lower costs are achieved because the service is implemented on standard electrical lines. The service is also convenient because it is already in many homes in urban as well as rural areas. Internet access through power line would be at several Mbps, which may be 20 to 50 times faster than a standard phone/modem connection. Most high bandwidth Internet access schemes fail at the point of connection to residences and businesses. The cost of connecting many individual points usually overwhelms the project. Power line services are already connected to almost all residences and businesses through electrical lines, thus making the service more economical for both providers of the service and customers of the service.

Using electrical lines makes the service very convenient. There is no need for the bulky apparatus associated with wireless access. The service does not tie up phone lines like standard phone/modem connections, current implementations of Cable TV services, or other phone line based services. Additionally, the system features constant access to the Internet and much of the apparatus is already in your home. Power line offers very high speed Internet access. Its performance far outclasses phone/modem connections and even ISDN. At 1Mbps, customers of power line services could explore the Web, talk on the phone, and watch a video-on-demand movie at the same time. All of these services are available through the innocuous looking electrical lines currently in your home. Evidently electrical lines were manufactured with more forethought than phone lines.

1.4 THE POWER LINE CARRIER SYSTEM AS USED BY ENERGY INDUSTRIES

Power line carrier links form the information transmission backbone of many electrical energy supply authorities throughout the world. The system, abbreviated to PLCS, has been of great value in power system network control over the years, principally because it offers a relatively economical solution to many information transmission problems. Among the signals which can be transmitted securely and reliably by means of PLCS are speech, teleprinting, telemetry (data), remote control (telecontrol), regulation, meter reading and most important, line protection signals [7].

To understand more fully the description of a PLCS and its associated components, it may be pertinent to describe briefly the power distribution system of the Electricity Supply Commission (Escom) in the republic of South Africa.

Escom is subdivided into a number of licensed areas of supply called Regions. Each of these regions has its own organization for construction projects and maintenance work and Control Centre, which is responsible for switching operations on the power network within that particular region. Each Regional Control Centre is tied to a National Control Centre at Simmerpan near Johannesburg. Also within each region are a number of substations and, in some cases, power stations.

These Power or Generating stations mostly situated in the Republic, supply electrical energy to the interconnected grid and this power is then distributed to the consumers within each Region.

Without going into detail it should be evident to the reader that the complex system of power distribution outlined above could not be satisfactorily monitored, controlled and protected without an efficient information transmission system. Such a system is required between stations, between control centres and stations and of course between National Control stations and Regional Control Centres. In most of these cases, power lines exist between such as stations, which in physical form consist of one or two three phase lines suspended by means of insulators from steel towers. Because these "hard wire" links are already in use for the distribution of power, such a system lends itself, with some necessary adaptation and interfacing, as a communications link. Hence the evolution of the Power Line Carrier System (PLCS) [6, 7].

1.4.1 What Is A Power Line Carrier?

Just as in a radio system a low frequency (audio) signal is modulated and then propagated as high frequency signal through free space by means of an antenna to some distant receiving antenna, so is a power line carrier signal (audio frequency) modulated and propagated as a high frequency signal along a power line. The text that follows describes in simple terms the basic operation of such a system and some of the techniques and problems associated with coupling the high frequency, low power carrier signal to a high voltage 50 Hz power line. While it is not the intention of the author to dwell on quantitative values, it may be of interest to point out, for comparison purposes, typical magnitudes of power and voltage associated with a typical power line and a typical power line carrier unit.

Typical Power Line

Phase to phase voltage	-	400kV
Phase current	-	2000 Amps
Power (neglecting phase angle)	-	800 kW
	-	89dBm
Frequency	-	50Hz

Typical Power Line Carrier

Output voltage	-	40V
Output power	-	40W
	-	46dBm
Frequency	-	200 kHz

1.4.2 Description Of A Power Line Carrier System

The block diagram in Figure 1.3 shows the simplest form of PLC transmission system in which the carrier equipment is coupled to a single phase of one power line. This is known as phase to ground coupling. Other forms of coupling, which will not be described in details at this point, include phase to phase coupling between two phases on the same line, and coupling between phases on two different lines, known as intercircuit coupling.

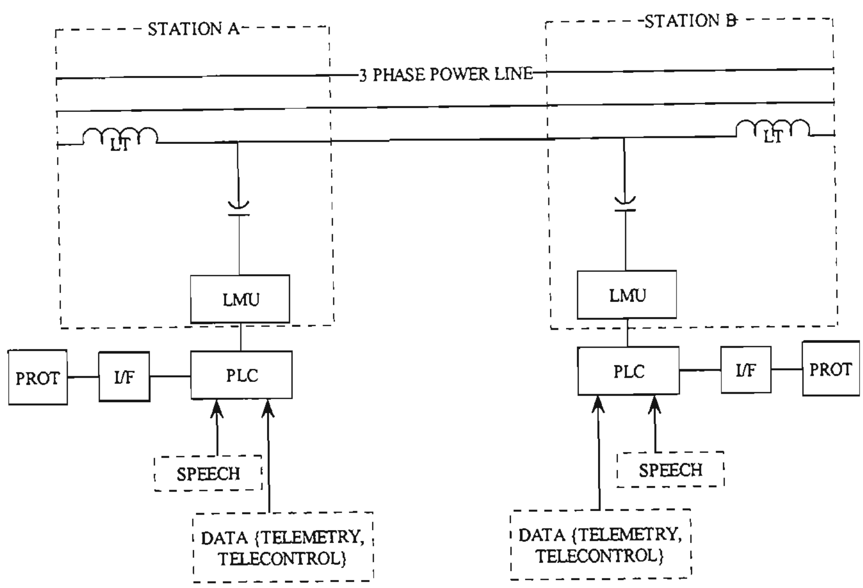

Figure 1.3: Block Diagram of Power Line Carrier System Coupled phase to ground on a Single 3 Phase Line (Eskom Transmission [7])

Key: LT	:Line Trap	I/F	: Interface Equipment
CC	:Coupling Capacitor	LMU	:Line Matching Unit
PROT	:Line Protection Equipment	PLC	: Power Line Carrier

1.4.3 The Power Line Carrier Unit

Fundamentally, the power line carrier unit consists of a transmitter and a receiver, usually housed in a common cabinet, together with the necessary circuitry required for interfacing the protection equipment and other inputs to the carriers. Also include in such a cabinet is the protection signalling unit should carried protection be a requirement for a particular line, which is usually the case for lines of 132-kV and above. It should be noted that in some cases power line carriers are used purely for speech and data transmission and as such are not equipped with protection signalling equipment.

The frequency bandwidth of a power line carriers is 8 kHz, a separate 4 kHz range being used for transmitting and receiving, these two ranges are however usually adjacent to one another. This 4 kHz bandwidth is subdivided into two frequency ranges, separated by means of sharp out-off filters, for speech and super audio or data information as shown in Figure 1.4. Depending upon the type of carrier equipment, other particular frequencies also occupy this bandwidth. For the purpose of explanation, certain aspect of the siemens ESB 400 PLC will be described. This system is, in the true sense of the word, a single sideband (SSB) system as the HF carrier is completely suppressed in the transmitter.

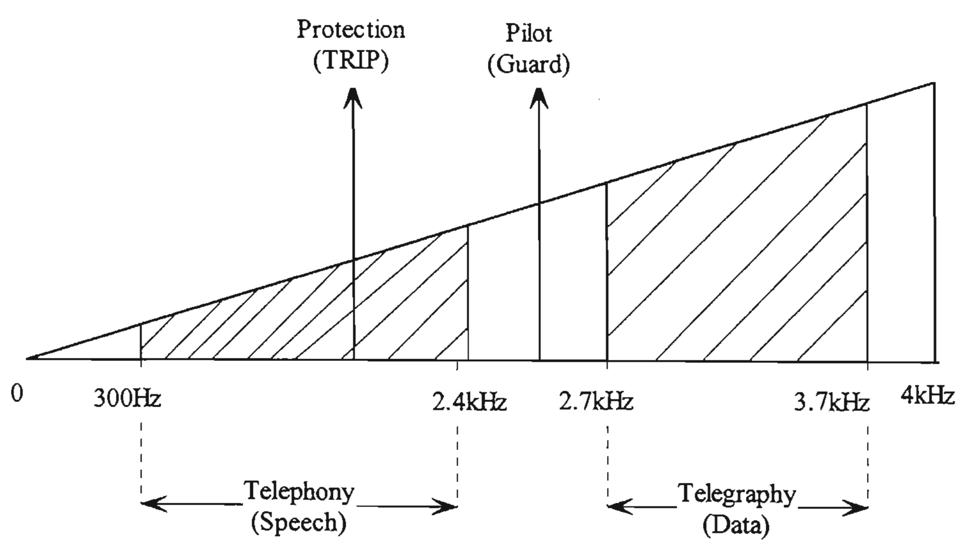

Figure 1.4: Subdivision of the 4 kHz channel (Eskom Transmission [7])

The subdivision of the 4 kHz channel shown in Figure 1.4 is as follows: -

i. A speech channel with a bandwidth of 2.1 kHz from 300 Hz to 2.4 kHz.

ii. A combined pilot and signalling frequency (which can be shifted – frequency shift keying – FSK) 2580 Hz.

iii. A super audio channel with a theoretical bandwidth of approximately 1 kHz.

iv. A protection channel capable of transmitting one or more independent intertrip signals.

The telegraphy channel is capable of accommodating a number of data channels for example 5x50 bd, 2x100 bd or 1x200 bd, where bd stands for band and means bit/second.

The simple block diagram in Figure 1.5 illustrates the interconnection of the transmitter (Tx) and receiver (Rx) units.

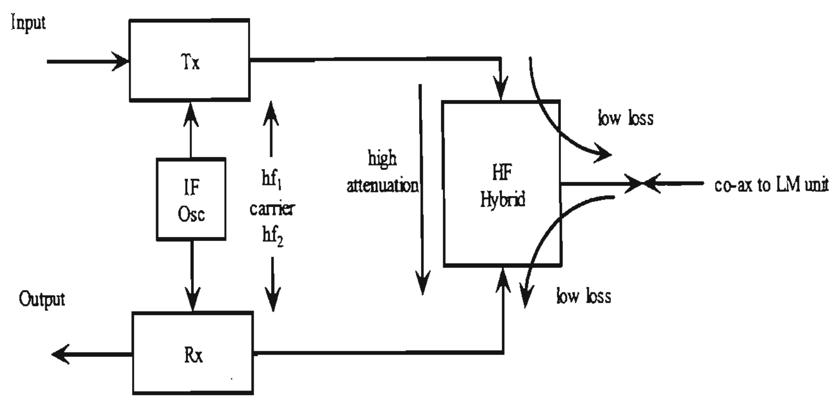

Figure 1.5: Interconnection of the transmitter to receiver units (Eskom Transmission [7])

A hybrid, connected to the output of the transmitter and to the input of the receiver, acts as a 2 to 4 wire converter since the coaxial cable from the power line carrier equipment is the path for both the transmitted and the received signal, e.g. input and output. This hybrid also provides a low loss path in the directions transmitter to line and line to receiver but blocks the transmitted signal from entering its own receiver.

Two stages of modulation are usually employed, the low frequency signal, 0 – 4 kHz is modulated in an intermediated frequency (IF) stage to around 20 kHz. (The TX and RX in the Siemens equipment share a common IF oscillator).

This signal is then modulated in the final stage of the transmitter to the desired HF frequency, typically between 50 kHz, from where it is fed via filters and a hybrid, co-axial cable, and the line matching equipment to the H.V. line. The converse takes place on the receive side, the output from the receiver occupying the adjacent 0 to 4 kHz channel. Figure 1.6 illustrates these concepts.

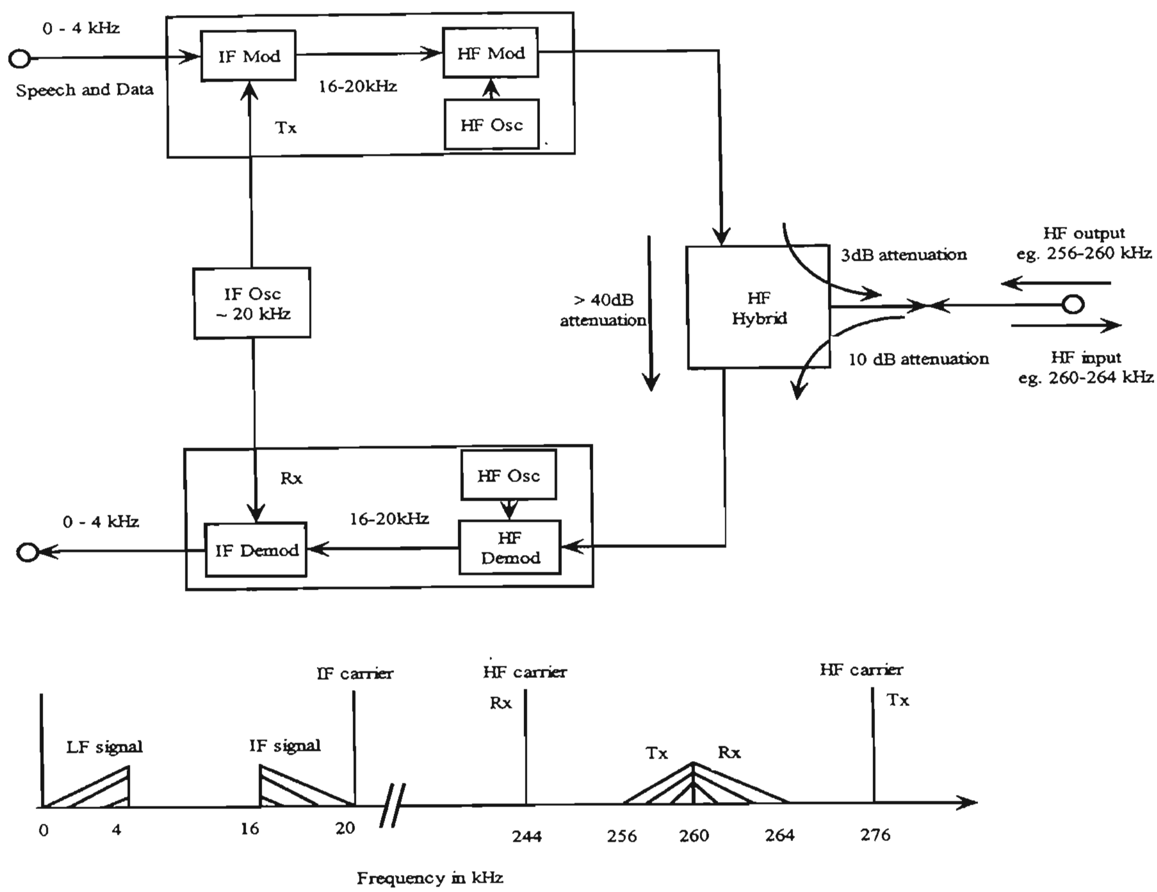

Figure 1.6: A detailed interconnection of the transmitter to receiver units (Eskom Transmission [7])

(For simplicity the low frequency spectrum is illustrated as a single 0 to 4 kHz band)

It may be relevant to mention a few aspects for the protection of HV lines. As the reader will appreciate, the amount of energy associated with equipment operating at say 400kV, and carrying currents of up to 2500 A, is substantial. However, under fault conditions details of which will not be discussed here, currents of hundreds of kilo amps may flow. These currents, if not arrested within a few milliseconds, will cause a great deal of damage to equipment and plant. The purpose of line protection, in whatever form, is to open the correct circuit breakers, and isolate faults as soon as possible after onset of the fault condition. Normal distance relays will clear a fault in a time of, for example, 100 to 300 ms, which is often not fast enough so a power line carrier system is used which facilitates the clearing of a fault in say 30 ms. Manufacturers are striving to reduce these times still further. The main consideration when designing a protection scheme is a high degree of reliability and security.

If the power line carrier is to be used for the protection of a high voltage line it is equipped with a protection-signalling unit. This consist of a transmitter which transmits a protection signal, usually a particular frequency within the 4 kHz channel, through the power line carrier unit, and a receiver which processes the received breaker trip signal and via some interfacing circuitry, uses it to operate a relay which in turns applies a voltage and opens a circuit breaker in the HV yard. The transmitter receives the command to transmit the breaker trip signal to the remote as follows (see Figure 1.7): -

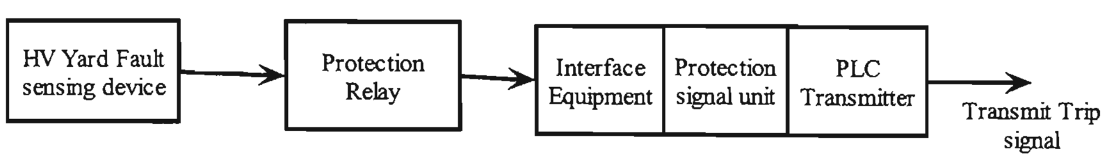

Figure 1.7: Sending of a trip signal (Eskom Transmission [7])

Whereupon the distant receiver processes the received trip signal which opens the required breaker (see Figure 1.8).

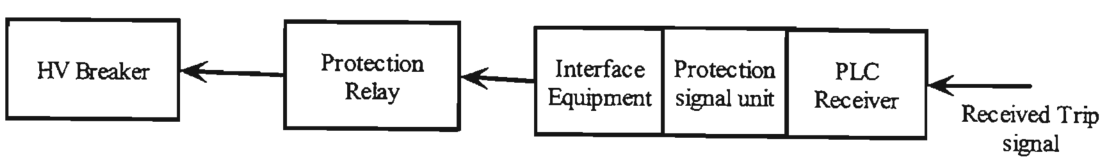

Figure 1.8: Receiving of a trip signal (Eskom Transmission [7])

The function of the interface equipment between the protection relays and the power line carrier equipment is to isolate the relatively high voltage signal (110 or 220 V dc) produced by the relays from the delicate electronics inputs circuitry of the power line carrier.

Most power line carrier transmitters cut the speech and data signals and boost the level of the transmitted trip signal by 6 to 10 dB, during the transmission of the trip (protection) signal, the duration of which is up to a few tens of milliseconds. The reason for this is that during certain fault conditions on the line, the noise level increases dramatically, so to maintain a reasonable signal to noise ratio, which will ensure correct receiver operation, all available power is channelled onto the line in the form of the trip signal. This signal is propagated over the power line to the remote end, where, via the appropriate equipment, the breaker is opened.

1.5 POTENTIAL AND DIRECTIONS FOR NEW APPLICATIONS AND SERVICES

This new technological and commercial environment will create vast new opportunities for everybody and especially for the power utilities. A new type of '*telecommunications plus energy operator*' is emerging which will grow out of a mixture of the old type monolithic telecommunications operators and old type power utility companies. This new type of operator is expected to gradually replace the existing ones, eventually taking the shape of a customer '*Services Operator*'.

This business development implies that the integration of ICT in energy systems is a strategic technological area. Here, Power Line Telecommunications will have a dominant role. Communication in general will enable the utilities to refocus their strategic intent, change their organization and improve their customer orientation and marketing. Current utility objectives are:

Cost reduction: - improve operations efficiency
- increase productivity
- improve asset utilization

- outsource non-core functions

Customer retention: - improve customer services

- retain revenue and load
- maintain competitive position
- gain new customers

New revenues: - develop new service offerings to both new and existing customers

- enhance services through communications functionality

Many of these are using PLT-enabled applications and services to help achieve their business objectives. Below we list a range of such PLT-enabled services that are currently being investigated and tested in Europe and elsewhere [69, 70].

Examples of operations-focused services

- automated meter reading enables the utility to remotely obtain meter readings, load and consumption data, and detect tampering and/or energy theft
- remote connect/disconnect for example, create a final read bill while the customer is waiting
- multi-utility services provide service bundles for other utilities
- network control operating efficiencies are targeted through automation of the distribution network, allowing dispatchers or computer-based algorithms to operate field devices to optimize the network (substation automation, dynamic loading and Volt/Var control)
- outage handling detect outages automatically and proactively notify customers in addition to service restoration
- power quality monitoring such as line conditioning to ensure that the service is delivered according to set performance standards
- predictive maintenance based on condition rather than on and field force automation time

Examples of customer-focused services

- aggregated, tailored billing for a number of customer premises
- appliance management individual appliances can be monitored and managed. Customer can be informed if appliance has abnormal usage or appears inefficient compared to modern alternatives
- customer load management electricity consumption based on time of use and/or real-time pricing in response to economic signals that provide incentives for more efficient use of energy; direct load control may be included as an option
- energy usage management the customer information interface is used to provide energy usage information and advice, as well as communications regarding billing and new services offerings
- interactive services customer interface for enabling service delivery, scheduling services appointments and selecting service options
- market pricing/availability market information regarding available options provided by the utility and/or other providers
- comfort and savings intelligent home devices and network agents providing home comfort and energy/cost savings functions
- Telecom intensive applications Fast Internet access (>2Mbps), electronic commerce, IP telephony, Web TV, electronic content services in education and entertainment, etc.

Today, the utilities are all working to prepare for the upcoming deregulation and to prepare for the open domestic market. Especially in the domestic market, information systems will be needed to handle the massive change into new flexible billing systems and systems that provide enhanced customer service. These systems must not only provide services towards the customers. The need is also to develop and focus on the utilities' own internal efficiency. A number of ways are considered to cut management and operational costs and to shorten repair times. Over the years 1980 - 1990, many utilities reduced personnel and have today reached the level at which only limited changes in this respect would be possible. The next step therefore is to incorporate more efficient methods through better information management and through up-grading old ICT systems [69, 70].

There is a trend to focus on increased efficiency, both when it comes to handling the customer services and to run the installations in an optimized way. Management based on condition rather than on time is one fast expanding area. Asset management is seen as the area in which it is possible to provide the greatest potential for reduced costs and increased efficiency in management and maintenance. Up till now, the SCADA systems – Supervisory Control and Data Acquisition - have been installed on higher system levels i.e. from production down to 50 kV. With the new communication and computer possibilities, the observation and control platform has been expanded to include the whole electric system, incorporating also some parts of customer systems/units. The power grid for data communication is essential for this approach.

As an example, analysis of British utilities show a total predicted investment of close to 2 billions ECU in ICT systems over the next few years, of which half will be related to customer and market systems. Those investments have been estimated to be allocated to the main sectors as follows [69, 70].

Call centres: 30%
Customer databases: 30%
Billing and transactions: 25%
Smart cards: 5%
Remote metering: 5%
Maintenance: 5%

Of the total ICT investment, the build-up of new telecommunications infrastructures is an essential part whereby the power lines will yield advantages provided that the data transfer is secure and efficient. All in all, from the viewpoints of both increased operational efficiency and enhanced customer service, it is evident that ICT is a strong competitive factor for tomorrow's energy and electricity industry, as it is for today's telecom industry [70].

1.6 PROJECT OBJECTIVE

The primary objective of this project is to evaluate the performance of the power lines (in terms of speed, access and bandwidth) and its applications, if used as a high speed large-scale data transmitter and information carrier in its own right as compared to most commonly used wire lines such as the xDSL and Cable TV. The secondary objective is to check its viability in rural telecommunication.

1.7 DISSERTATION STRUCTURE

Chapter 2: The focus of this chapter is on the comparison of the types of access technologies available or proposed for rural telecommunication. Their merits and demerits are weighed up leading to the proposing of a power line communication system as an alternative network for communication in rural areas.

Chapter 3: Global deployment of the power line technology and problems encountered are discussed in this chapter. Regulations and applications proposed by telecommunications authorities are also looked at.

Chapter 4: Chapter 4 looks at the power line as a communication medium in its own right. The focus is more on the transfer function of the channel, frequency characteristic, limitations in terms of frequency spectrum, bandwidth and attenuation, how channel generates harmonics, influence of loading and services of PLC are discussed in this chapter.

Chapter 5: A typical power line design for communication purposes is done and explained in this chapter. The channel is characterised by a channel transfer function $H(f)$ and a subsequent additive noise term based on the OFDM transmission technique.

Chapter 6: Numerical and simulations results and also the discussion of these results is done in this chapter. Attenuation factor $a=10^{-7}$ and $a=10^{-6}$, bandwidth of 2 MHz and 3 MHz are used to evaluate channel capacities, BER and SNR. Practical set up is also discussed but using GMSK as a modulation scheme. Finally a solution to rural telecommunication is proposed.

Chapter 7: Conclusion, recommendation and future research are done here.

CHAPTER TWO

COMPARISON OF WIRELINE TECHNIQUES

2.1 WIRE LINE COMMUNICATION

The last mile, first mile, local loop, access network: Whatever you choose to call it, the meaning's the same, that part of the telecom network that links users with broadband services. There are many techniques to do that and this chapter tries to cover some of them.

Traditionally basic users have used a modem connected to PSTN to access the Internet. There are many emerging solutions to the faster last mile access: ISDN, ADSL, Cable modems, hybrid fibre coax, fibre-optics, etc. Broadband was the mantra of the dot-com and telecom booms, and is being offered as a magic elixir for curing the woes of the high tech sector. There are interesting dynamics to the financial and technological scenes that suggest broadband access may arrive very soon to very many people. Fibre-to-the-home, widely regarded as the Holy Grail of residential broadband, might never become widespread, because of other competing technologies that make the use of existing infrastructure [8].

2.2 ISDN (INTEGRATED SERVICES DIGITAL NETWORK)

ISDN (Integrated Services Digital Network) is a digital telephone line which allows normal telephone operation and data communications at speeds of 64 kbit/s and 128 kbit/s using normal home telephone wire. Using the same copper phone line that modems use, ISDN delivers a considerable speed improvement up to 128 kbps and provides essentially perfect transmission reliability. And ISDN can mesh into other digital technologies, such as Frame Relay and ATM, making possible future speeds several times higher even than 128 kbps.

The "Integrated" part of ISDN's name refers to the combining of voice and data services over the same wires, so computers can connect directly to the telephone network without first converting their signals to an analogue audio signal, as modems do. This integration brings with it a host of new capabilities combining voice, data, fax, and sophisticated switching. And because ISDN uses the existing local telephone wiring, it's equally available to home and business customers. Most important for Internet users, however, is that ISDN provides a huge improvement in access speed at only a fractional increase in cost.

ISDN service is available today in most major metropolitan areas and almost throughout the country in USA, Canada, Far East and in most European countries. They are also widely available in urban areas of South America, Middle East, Northern and Southern Africa. Many Internet Service Providers (ISPs) sell ISDN access. The ISDN connection price depends on your local telephone company, equipment budget, and ISP. An Internet ISDN connection consists of three components: the ISDN line itself, the equipment and the ISP's fees.

ISDN provides a raw data rate of 144 kbps on a single telephone company (called Telco in the business) twisted pair. To better suit voice applications, this 144 kbps channel is partitioned into sub channels: two 64 kbps B (for bearer) channels and one 16 kbps D (for data) channel. Each B channel can carry a separate telephone call and usually has its own telephone number, called a Directory Number (DN). You can combine the two B channels together to form a single 128 kbps data channel through a process called bonding. The B channels carry customer voice or data signals. The D channel carries signals between the ISDN equipment and the phone company's central office. The two bearer plus one data channel is called the Basic Rate Interface (BRI) or sometimes just 2B+D.

Because ISDN is purely digital, the telecommunication companies can more easily deliver data intact from end to end, largely eliminating the effects of noise. And because the 64 kbps channel is essentially a pure "bit pipe," with no rate negotiation or handshaking involved, there are no modem speed or protocol differences to cause conflicts. In fact, because the negotiation phase with ISDN is so simple, ISDN takes only a second or two to dial and establish a connection (modems may take as long as a minute to accomplish the same thing).

2.3 DSL (DIGITAL SUBSCRIBER LOOP)

DSL (Digital Subscriber Line) is a new, digital data-connection method that allows high-speed Internet connections over standard telephone lines. A standard telephone infrastructure around the world consists of a pair of copper wires that the phone company installs in your home. A pair of copper wires has plenty of bandwidth for carrying data in addition to voice conversations. Voice signals use only a fraction of the available capacity on the wires. DSL exploits this remaining capacity to carry information on the wire without disturbing the line's ability to carry conversations.

To use DSL, a DSL modem or DSL router is required. They work with the same single-copper-wire pair that telephone services use, but they contain sophisticated digital signal processors that take advantage of a much greater range in the frequency spectrum. The result is much higher bandwidth capability than standard telephone service and modem combinations. There are many related technologies like HDSL, HDSL2, ADSL, SDSL, RADSL, VDSL and many other which are commonly referred to as DSL or xDSL technologies [6].

2.3.1 ADSL (Asymmetrical DSL)

ADSL (asymmetrical DSL) is a DSP-based communications technology that can dramatically increase the speeds of data communications over the typical copper wiring that connects most homes and businesses to the public telephone network. ADSL can transfer data up to megabits per seconds speed and is particularly well suited to Internet-related communications. DSL normally only works within a certain distance (typically 5500 metres) of the telephone company central office and is therefore unusable for many rural and semi rural customers. The performance (data rate and error rate) of DSL depend on used wiring conditions (line length, line noise, etc.) and the used DSL technology.

For loops beyond 5.5 km, the signal loss at frequencies above 1 kHz is excessive, making voice transmission unacceptable. Series inductors (typically 88 mH) placed at 1.8 km intervals result in flatter frequency response across the voice band at the expense of much greater loss at frequencies above the voice band. As a result, DSLs will not operate on loaded loops. Figure 2.1 illustrates the effect of loading on frequency response. In the 1970s, prior to the massive deployment of digital loop carrier, 20% of loops were loaded. In rare cases, loading coils are found on loops shorter than 5.5 km. To permit DSL operation, loading coils may be removed. However, an expensive effort is required to find and remove the loading coils. In Europe, loops beyond 5.5 km are rarely found, so loading coils are not used.

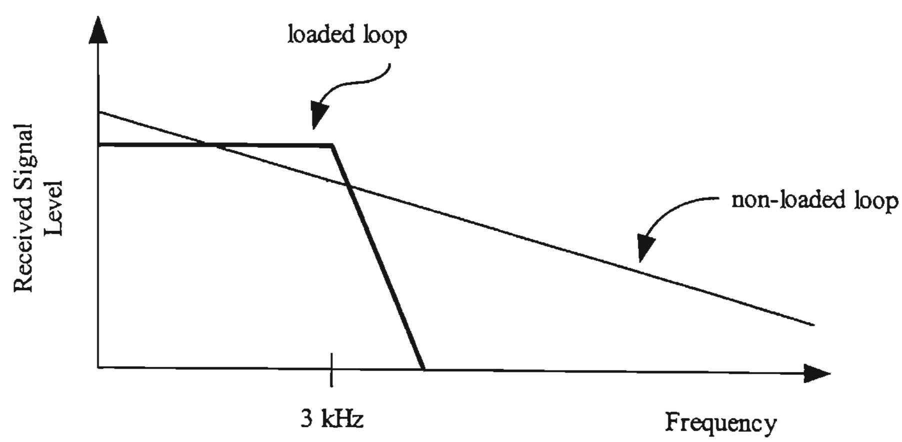

Figure 2.1: Loaded loop frequency response

ADSL is the most common technology used to provide broadband Internet connections to homes and small offices. This technology offers potential to up to 6.8 Mbit/s downlink (256k or 512k being typical speeds used) and uplink speed up to around 700 kbit/s (typically 256k or 368k) [7, 8 & 9]. ADSL technology can coexist in the same line with normal analogue telephone line (PSTN). When the same line is used for both ADSL and PSTN, some special filters are needed between the line and PSTN devices to filter out the

ADSL high frequency signals from entering those devices. ADSL can not coexist on the same line with ISDN system because they operate at same frequency range. ADSL connections are always built between the terminal device on the user premises (ADSL modem) and the central office device (ADSL DSLAM).

2.3.2 SDSL (Symmetrical DSL)

Symmetrical DSL (SDSL) is a technique which transports fast digital signals through telephone line wiring. SDLS system transfers the data at the same speed to both directions (typically from 256 kbps to few megabits per second) through telephone line wiring. Two suitable SDLS modems can be connected to each other through some kilometres (typically below 5-10 km) of telephone line (leased line).

2.3.3. VDSL (Very High Bit Rate DSL)

The newest competitor in the field is VDSL. VDSL stands for very high bit-rate DSL. It is seen by many as the next step in providing a complete home-communications or entertainment package. VDSL provides an incredible amount of bandwidth, with speeds up to about 52 megabits per second (Mbps). VDSL's amazing performance comes at a price: It can only operate over the copper line for a short distance, about 1200 metres. As from the year 2002, products seemed to be still limited to around 15 Mbit/s speeds.

DSL is a distance-sensitive technology, as the connection's length increases, the signal quality and connection speed decrease. ADSL service has a maximum distance of 5460 metres between the DSL modem and the DSLAM, though for speed and quality of service reasons, many ADSL providers place an even lower limit on the distance. At the upper extreme of the distance limit, ADSL customers may experience speeds far below the promised maximums, whereas customers close to the central office or DSL termination point may experience speeds approaching the maximum, and even beyond the current limit in the future.

2.4 CABLE TV DATA

Many traditionally one-way cable TV networks have nowadays converted to two-way data highways by adding two way operation to the cable TV network amplifiers and connecting cable modems to the cable TV network. Cable modems are devices that allow high-speed access to the Internet via a cable television network. While similar in some respects to a traditional analogue modem, a cable modem is significantly faster.

There are different cable modem systems in use. Some cable companies have "one-way" cable modem service. In this system, communications in the down direction is by cable but the return path is by conventional telephone line and telephone modem (33 kbps). Two way cable systems transmit data in both directions via cable and therefore do not need a telephone line. Uplink speeds are typically higher than 56K modem but not as high as downlink speeds. Downlink speeds are typically at least several hundred kilobits per second.

Cable modem service is typically provided as always-on service. A "Cable Modem" is a device that allows high-speed data access (such as to the Internet) via a cable TV network. A cable modem will typically have two connections, one to the cable wall outlet and the other to a computer (PC). Most cable modems are external devices that connect to the PC through a standard 10Base-T Ethernet card and twisted-pair wiring. Cable modem speeds vary, depending on the cable modem system, cable network architecture, and traffic load. An asymmetric cable modem scheme is most common and is specified in the DOCSIS, EuroDOCSIS and DVB Euro Modem standards. The downstream channel has a much higher bandwidth allocation (faster data rate) than the upstream.

The dominant service offered by cable modem is high-speed Internet access. Many cable TV operators are packaging high-speed data services much like they do basic cable television service.

Cable modem systems are generally implemented as a very asymmetrical system. There is fast download and slower upload. All the network traffic is controlled by the operator system, it gives different modems rights to transmit and control what they receive. The cable modem systems are generally built so that the user cable modem can only communicate with the access router in the operator premises. This device then forwards the traffic to where-ever the user wants to communicate and the operator policy allows.

2.5 POWER LINE COMMUNICATIONS

Power line Carrier is a communication technique that uses the existing power wiring (120 Volts, 240, etc) to carry information. It is a kind of "wireless" means of communication, because PLC technology can supersede the installation of dedicated wiring in some applications. Various applications use PLC technology from power company equipment controlling to computer networking. The two main reasons why there will be communications problems with PLC transmissions are low signal level and noise or interference.

Typical frequency ranges used in power line communication is from 30 kHz to 150 kHz. In Europe mains power line communication is standardized at 1991 in EN 50065-1 standard. EN 50065-1 is defined to standardize signalling on low-voltage electrical installations in the frequency range 3 kHz to 148.5 kHz. It gives general requirements, frequency bands and electromagnetic disturbances. The frequency range of EN 50065-1 is split to four different frequency bands. In the A-band, the carrier signal can be from 9 kHz to 95 kHz where electricity suppliers and their licensees are permitted to communicate. Power lines can also be used for other applications; the C-band is for consumer use with an access protocol. This band goes from 125 kHz to 140 kHz. Between the A-band and C-band is the B-band, used for consumer without an access protocol so this band has some freedom of communication. Devices can interfere with one another and baby alarms use this band.

Above 150 kHz, communication is prohibited in Europe. But in USA those higher frequencies are usable. Popular "wireless" intercom systems for example operate at around 150 kHz to 500 kHz frequency range.

The power line environment is a hard environment for any communication. For example vacuum cleaners, hand-held drilling machines, etcetera which use universal series wound motors generate a lot of impulse noise to power line. TV-sets are a very common source of distortion. Light dimmers are also a source of mains noise. Switch mode power supplies use high frequency components, and usually a lot of tonal noise is generated. Everything can change over the frequency range, both the attenuation, phase response and noise level. The channel response (amplitude and phase) between any two nodes on the power line varies greatly with frequency; at some frequencies the signal is attenuated such that it is lost below the ambient noise floor. Figure 2.2 shows a noise power spectrum density in good and foul weather respectively (foul weather in this case is referring to lightning and thunder storm). As a further complication, the noise and channel response of a power line network vary over time. Generally, the channel's characteristics are stable over the time required to send numerous packets [16]. If a packet is lost due to changes that occur during transmission, the packet is re-transmitted.

To compensate for these effects, this work explores signals using a frequency band from 2 to 20 MHz as proposed in the Part 15 of the FCC rules. Spreading the signal out over a wide band increases the probability that a portion of the signal can be received

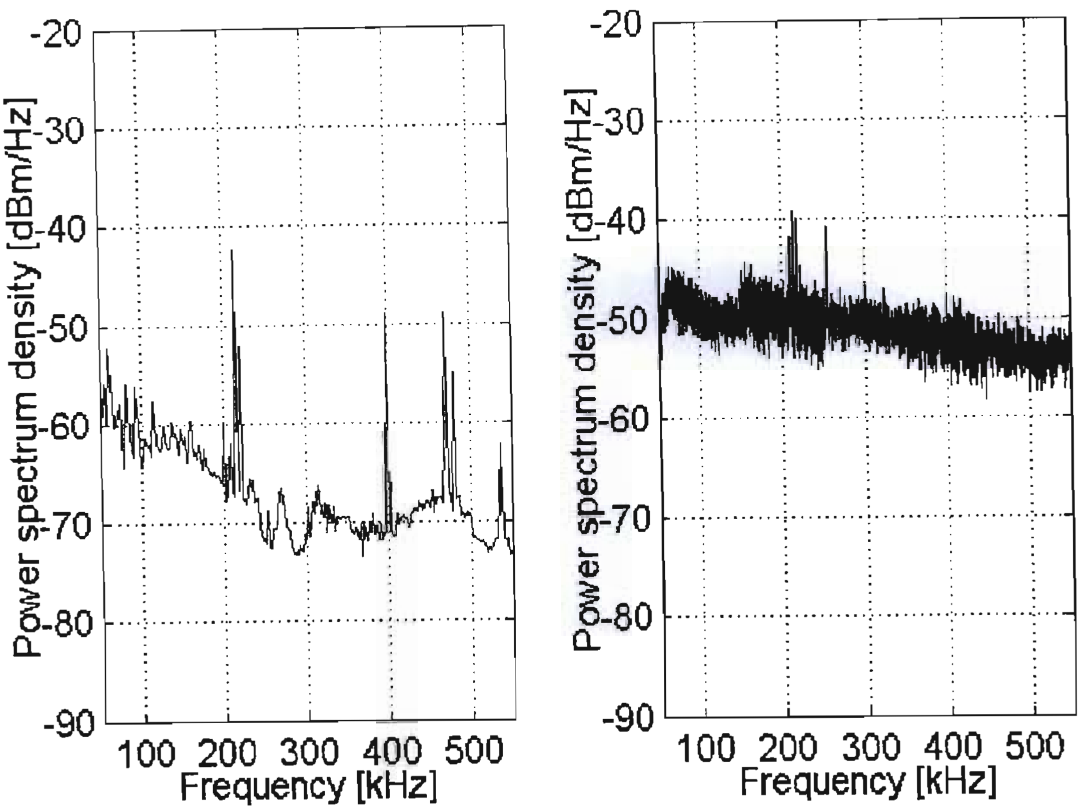

Figure 2.2: Noise Power Spectrum Density in good weather (left) and foul weather (right) (Eskom Transmission [7])

Broadband over Power Line (BPL) is a form of power line carrier technology that uses existing low and medium-voltage power lines to deliver broadband services to homes and businesses. BPL proponents, primarily electric power utilities, are testing BPL systems in several markets. BPL uses frequencies between 2 MHz and 80 MHz. Radio amateurs fear that BPL could affect HF and low-VHF amateur allocations wherever it's deployed. The problem in using the open wire medium voltage lines is potential radio signals radiation out of the wires. Electrical transmission lines were designed to conduct 50- or 60-Hz power from point to point. At those frequencies, power lines are excellent transmission lines and little of that 50- or 60-Hz power is radiated. The electric-utility industry also uses those lines at frequencies below 490 kHz to transmit Power Line Carrier signals to control utility equipment. Those lines, however, were not designed to carry radiofrequency energy. As the frequency of carrier-current signals conducted on power lines is raised, the amount of signal radiated from the line increases rapidly. The gain of the power-line as a radiator increases rapidly with frequency. A radiating conductor with relatively low emissions at 0.1 MHz can have emissions tens of dB higher at HF.

2.6 COMPARISON BETWEEN VARIOUS ACCESS TECHNOLOGIES

In order for one to understand the merits and demerits of access technologies, we look at home networks as an example. Once the decision to add a home network has been made, consumers will expect it to be easy to install, reasonably priced, and require low-maintenance. There are currently three broad categories of home networking technologies: special network wiring such as CAT5, co-axial cable, or telephone lines, wireless networks, or power line networks. Refer to Table 2.1 for a review of these three alternatives. While each of the alternatives has its appeal, most homeowners will want a solution that is easy to install and easy to use. They do not want high maintenance. They do not want to disrupt their homes to put the network in place, pulling cable through the walls or punching holes for jacks. They do not want to have to open their PC or other device and screw in cards. Most car owners do not do their own maintenance but they do like to drive. Plug and play is the preferred mode of use.

Network comparison at a glance

	Special wires	Wireless	Power line
Pros	- Dedicated connection	- Nodes available almost everywhere	- inexpensive - built-in encryption for security - many nodes available - single standard
Cons	- needs new wires - difficult to add nodes - expensive to retrofit	- added cost to devices - older hardware needs adapter - no single standard - possible security issues	- not ideal for handheld devices

Table 2.1: Network comparison at a glance (Source: Spectrum [3,72])

There must be adequate connection points available. The number and location of special wiring nodes must be specified at the time of construction and it is not easy to foresee all the applications the network will have to support in future. Finally, the cost must be reasonable. Adapting older devices and adding new network nodes add to the expense of installing a home network.

Power line networks provide the consumer with a low cost, convenient option. As with phone line networks (and other networks using special wires), no antennae or RF conversion hardware is required, making power line inherently lower in cost than a wireless solution. Using power lines for a home network provides many connection points for network devices.

As most devices will require a power source, the outlet is a convenient connection point. Power line networks use a single industry standard to ensure that all power line network devices will be interoperable. There are several alternative technologies, besides PLC, for the provision of the Information Society local access infrastructure and services. Each technology has its own strengths and weaknesses. A state-of-the-art comparison between PLC and some other relevant technologies is presented in Table 2.2.

Copper / PSTN

+ Mature and robust
+ Good installed base
+ Wide choice of product
+ Easy to install / use
+ Relatively cost effective

– Relatively slow
– On demand only

ISDN

+ Mature and robust
+ Widely available

– Expensive for consumer market
– On demand only

Cable Modems

+ Excellent performance
+ Permanently on line

– Limited geographical coverage
– Currently only available in limited trials
– Contention based

Copper / ADSL-Lite

+ Good Performance
+ Currently at the trial stage
+ Permanently on line

– Immature
– Length of local loop affects performance

PLT

+ Good Performance
+ Permanently on line
+ Good geographical coverage

– Still at the developmental stage
– No installed base
– Distance limited
– Possible problems in meshed power networks

Table 2.2: State-of-the-art comparison between PLC and other relevant technologies (Source: Mason Communications Ltd [10])

A technology comparison must not only take into account the state of the art today, but should also look at the ease of development and improvement in the near future. This is done in Table 2.3, which compares the upgrade paths for various technologies.

Customer Bandwidth

	COPPER / PSTN 1)	CABLE TV NETWORKS 2)	FIXED RADIO (WLL) 3)	POWER LINE TECHNOLOGY 4)
Broadband > 1 Mb/s	↑	↑	↑	+
Wideband 128 kb/s - 1 Mb/s	Introduction of ADSL	Introduction of cable modems	Introduction of broadband radio	+
Midband up to 128 kb/s	–	–	–	+
Multi-telephony (minimum data)	Requires additional build	Requires additional build	Requires additional build	+
Telephony (minimum data)	+	+	+	+

1) Copper twisted pair
2) Hybrid fibre coax with copper termination for telecoms
3) NORTEL proximity - 1 radio system
4) Based on OFDM implementation protocol

Table 2.3: Comparison of access technology upgrade paths (Source: Spectrum [3,72])

Hence, the upgrade path for PLC technology is highly attractive compared to other local access technologies in terms of implementation requirements. Other access infrastructures require significant capital investment to deliver more than one or two telephony lines. PLC systems are under development that will allow bandwidth delivery to increase incrementally as market demand requires. The technology comparison then shows that the major advantages of PLC technology are the following. It offers a permanent on-line connection without incurring the usage costs associated with conventional switched systems, and it has good performance and very good geographical coverage. Moreover, it provides symmetric, two-way communication. It is relatively cheap because most of the infrastructure is already in place, and has an attractive upgrade path [9, 10]. Finally, it is unique in that it might provide both telecom and value-added energy customer services at the same time. Currently, the main weaknesses of PLC technology are that it is still at the developmental stage, it has no significant installed customer base yet, the distances it can cover are limited, and possible problems may arise when very heavy power functions are simultaneously involved. It offers medium bandwidth, but not the extremely high bandwidths as some other technologies do, the latter however with higher costs and less coverage. In sum, PLC is a definite and significant last-mile local access technology, but it will not be the only one. The use of different complementary technologies is seen as more likely, since each technology offers a different compromise between bandwidth, reach, noise immunity, and cost. PLC has a number of unique advantages, but it must be positioned within a well defined local access strategy, especially targeting geographic concentrations of users requiring common services [11].

CHAPTER THREE

GLOBAL DEPLOYMENT AND PROBLEMS ENCOUNTERED

3.1 LOW-VOLTAGE AND MEDIUM-VOLTAGE ARCHITECTURES

Most early deployments of PLC access technology have placed the head end gateway at the low-voltage transformer site. This location provides stability and short distances within which to operate. The chipsets available so far have provided limited bandwidth and are unsuitable for sharing by large numbers of subscribers.

As PLC technology matures, the limitations of the low-voltage architectures become more noticeable. Back-haul costs and limited subscriber capacity become more significant issues the closer utilities move to commercial services. Furthermore, North America's electricity grid is characterised by small transformers serving small numbers of customers; this does not lend itself well to PLC deployment. Despite this and North America's greater penetration of broadband technologies such as cable and DSL, the region's high revenue potential makes it a key market in which to generate capital investment for the development of PLC [58, 63].

The alternative to low-voltage architectures is to move the headend gateways to a location at the substation on the medium-voltage lines. However, this approach faces significant challenges: it requires some form of bypass of the transformer units; it also needs high-bandwidth chipsets for service provisioning to larger groups of customers on the same gateway. The challenge of bypassing is usually tackled by using a coupling device; the need for bandwidth will be met by evolution of chipsets and prototypes.

At present, DS2 in Spain makes the highest-capacity chipset — bandwidth capacity of 45 Mbps with throughput of up to 13 Mbps. Ambient, the most prominent PLC system vendor in North America uses DS2's chipset. Most other vendors are reportedly working to expand the bandwidth capacity of their chipsets to between 10 Mbps and 20 Mbps [58, 63].

It is logical for PLC to evolve toward medium-voltage architectures over the next few years. The cost of providing back haul for headends is unlikely to fall significantly during this time and will continue to loom large as a deterrent to large-scale deployments of PLC where the utility does not own a back-haul network based on other technologies. Although low-voltage architecture provided a safe environment for PLC's early development, Gartner Dataquest doubts whether it can support PLC's evolution to large-scale business models worldwide [64].

3.2 INTERNATIONAL TRIALS

In North America, a transformer serves from 5 to 10 households while in Europe and India a transformer serves 150 households. Power line signals cannot pass through a transformer. Therefore, all electrical substation equipment needed for power line has to be located after the transformer. If there are fewer households per transformer predicted equipment costs would be prohibitive. However, this conclusion has been debated. Analysts suggest that 100% subscription rates are possible in US, and that at such rates power line is profitable [56].

Soon after the first trials of power line in the UK, some unanticipated problems arose. Certain radio frequencies were suddenly deluged with traffic, making it impossible to transmit on those frequencies. BBC, amateur radio, and the UK's emergency broadcasting service were affected. The apparent culprits were standard light poles. Then it became clear that by pure chance British light poles were the perfect size and shape to broadcast Power line signals. This situation posed problems not just because of the frequencies involved but also because anyone could listen in on the traffic. Companies are addressing the problem by proposing to lease the frequencies involved from their owners and offering amateur radio operators a new frequency. Negotiations on this topic are currently taking place in London [56].

Power line technology was first tested in a public setting at the Seymour Park Primary School in Manchester, UK. Twelve PCs were connected to a single Power line outlet. Dedicated high-speed access to the Internet turned out to be a great success in the eyes of students and teachers.

Nortel's power line web site quotes Seymour Head teacher, Jenny Dunn; "The high speed connection really lets us take advantage of the educational potential of the Internet. With a normal connection the children could lose interest waiting for pages to download. The new system means information arrives virtually instantaneously, thereby maximizing teaching time and keeping children on task. This set is amazingly flexible in educational terms, and not only gives us the additional medium with which to improve standards, but prepares us for the National Grid for Learning" [57].

Following the success at Seymour Park, a more comprehensive trial was initiated at the Stanley Road electricity substation, also located in Manchester. The crux of this trial was to test the limits of power line technology and make sure that it could meet industry standards even in worst case scenarios. The Stanley Road substation was set up to use two distributors to serve two distinct neighbourhoods. Northumberland Close is located 350 meters from the substation and Seymour Close is located 600 meters from the substation. Fifteen users were chosen between the two neighbourhoods to participate in the pilot program. They received various data and telephone services as well as remote metering/information services.

Unfortunately, the results of the trial are unobtainable. Nortel and Nor.Web claim that the results of this trial and similar trials in the United States are being protected for competitive reasons. The only indication of the trial's success is a subjective quote from Nor.Web. The quote states that "results produced over this period have now proved conclusively that Nor.Web's technology provides a commercially viable alternative to established means of telecommunications delivery to customer premises" [66].

German utility Energie Baden-Wurttemberg (EnBW) has launched a trial for Internet access over electrical power lines. The trial puts EnBW in the forefront of utilities looking to exploit the opportunity of Internet access over power lines. If utilities can iron out problems such as a transmission standards as well as disturbances during transmission, the technology holds out the promise of providing cheaper and faster Internet access than telephone wires. Power lines connect customers at 1 Mbps, prompting the utility behind the project, Energie Baden-Wurttemberg (EnBW), to promise no dial-ups, no hefty phone bills and no World Wide Wait.

EnBW is one of a consortium of power companies committed to using power line technology, which allows voice and data to be sent in both directions over electrical power lines at speeds of up to 1M bit per second. EnBW is working on the trial project with its telecommunications subsidiary, Tesion Communikationsnetze Sudwest, a joint venture with carrier Swisscom, Nortel Dasa, a joint venture between Canada's Northern Telecom and Daimler-Benz Aerospace of Germany, and Nor.web.

To link up to the Internet, customers use an Ethernet network card, which connects to a coaxial cable outfitted with a special modem. From there, data is sent on to a nearby electricity meter. Besides making possible Internet applications that require high bandwidths such as sending large data files with graphics and video, the technology may also be developed to automatically read users' electricity meters.

Using technology developed by United Utilities in 1995, Energie transmits digital data to and from a cable-modem-type device connected to a consumer's PC. The device is connected to a box attached to a home's electric meter that converts the signals and sends them over a power line. When the signals reach a power transformer, they're peeled off, transferred to a fibre-optic network and uploaded to the Net [65].

3.3 DOMESTIC TRIALS

The last mile in telecommunication is the term used for the link between a telecommunication service provider like Telkom or the Second Network Operator (SNO) and the end user. Currently these services or the last mile are being provided by Telkom by means of, mostly, telephone lines. With the SNO coming into play, Telkom will no longer have sole mandate over the provision of last mile services. However in the case of the SNO, the problem of bridging the last mile arises. It is just not viable for the SNO to roll out copper lines to each and every end user or subscriber in the same way that Telkom invested in their infrastructure over the last 70 years. It is for this reason that SNO at the City of Tshwane have been investigating several last mile access alternatives. One of the alternatives is power line communication (PLC). Power line communication - PLC Power line communication is not a new concept. It has been used by Eskom for telemetry purposes for a number of years already, at very low bandwidths/data rates. It is only recently that development in the field reached a level where broadband services such as telephony, high speed Internet access, video streaming, etc. can be supplied using the electricity network [67].

Power line communication works on the simple principle of providing voice and data services over the existing electricity infrastructure. Data and voice signals are injected into the network at a central point on the electricity network by means of some kind of PLC coupling device and the end user can retrieve these data or voice signals by means of a PLC modem. Two divisions of PLC exist currently: medium voltage (MV-PLC) and low voltage (LV-PLC). With MV-PLC the 11 kV electricity network is used for primary data distribution, whereas with LV-PLC the 380 V consumer distribution network is used. LV PLC is currently installed or being rolled out at various sites in Europe where electricity utility companies provide telecommunications services to their customers over the power lines using some or other kind of PLC technology [67, 68].

At Tshwane, Corporate Communications Department researchers currently have four installations where the possibilities of providing telecommunication services under license of the SNO are currently being investigated. MV PLC is still in the early stages of development and not much success has been reached in this field. The main reasons being that the general length of 11 kV cables is too great for the distance the injected signal can travel and some safety issues exists where the PLC equipment needs to be coupled onto 11 kV cables, switchgear or busbars. At Tshwane four pilot projects regarding PLC have already been rolled out. These include an office building, PLC in a laboratory, and two residential areas. In all four cases it was be shown that it is possible to provide last mile access via power lines [67].

A few PLC pilots have been rolled out in the last two years in South Africa by Tshwane and Eskom. The technologies tested up to date are ASCOM (Tshwane), Inovatech (Tshwane) and Main.Net (Eskom). All three pilot systems have been rolled out successfully and future pilots with Sumitomo, Ambient and others will also be investigated. A short summary of these pilot systems are listed below [67, 68].

3.3.1 Ascom Power Line Communication

The ASCOM PLC system has been successfully rolled out and tested by Tshwane during the course of 2002/2003 at various sites. The first pilot was at the Electronic Services offices in Tshwane. The Tshwane pilot was from a substation about 400 m away on overhead lines to the office building. The second pilot is in a laboratory environment at the University of Pretoria (UP), where ten computers are connected via the electricity infrastructure and PLC system. Data rates of up to 4,2 Mbps were measured in both the Tshwane and UP pilots. Thirdly the ASCOM PLC system is being used for the roll out of PLC in a residential area. With this pilot, broadband services are provided to a few residential homes.

3.3.2 Main.Net

The Main.Net PLC pilot was rolled out by Eskom TSI, their research division. The pilot successfully supplied Internet access via power lines to five residential users.

The minisub where the signal was injected was about 450 m from the furthest point in the PLC network. A constant data rate of 2 Mbps was shared amongst the five users.

3.3.3 Inovatech

The Inovatech pilot was rolled by Tshwane Municipality and is currently still running. It is rolled in the same way as described for the ASCOM Tshwane pilot above. Data rates of up to 18 Mbps (11 Mbps downlink and 7 Mbps uplink) were measured. This system also includes automatic meter reading whereby the meter data are also transferred via the power lines.

3.3.4 Other Trials

Other domestic trials are research trials done by universities (to name a few, University of KwaZulu Natal, University of Rhodes, University of Fort Hare and University of Pretoria). Observed measurements done by the CoE of the University of Fort Hare came to data rate of 3.67 Mb/s on the downlink and 4.72 Mb/s on the uplink using 3 streams. The equipment that was used was a 4.5 Mb/s ASCOM adapter. The distance between the measuring points was about 70 metres.

3.4 MARKET DIFFERENCES BY REGIONS

3.4.1 Europe

Europe is the leading market for PLC deployments and technical expertise. Europe's electrical grid consists largely of cells in which a single transformer supplies about 200 houses. This is a far better topology for PLC than that found in, for example, the United States, where a typical cell is only 20 houses. In practice this means that, in the United States, a utility company would have to deploy 10 times as many transformer head ends to "pass" the same number of houses. Also, Europe's electricity wires are, in general, better-shielded; this helps tackle radiation and noise problems. Broadband availability —

and even more so competition — is limited in many European countries. Typically, a given area has only one broadband supplier (if any). These monopolistic suppliers are keeping prices high and "skimming the market"; Europe has some of the world's most expensive DSL and cable broadband services [55].

Consequently, the overall penetration of broadband is very low, at less than 2 percent of households in Western Europe. There are, however, some country exceptions to this low-penetration rule. Research by Gartner Dataquest and Gartner G2 has revealed a strong connection between broadband penetration and service price: more households would subscribe if services were cheaper. This offers potential for PLC if its costs can be reduced and the service offered for less than $25 a month [61].

In fact, some PLC offerings already start well below this; in Germany, for example, PLC broadband services start from about 15 euros a month plus 120 to 150 euros for installation. Many PLC operators price their services by usage. For example, the first 100 Mbps cost a certain amount and extra charges apply for more. Such pricing models have typically not been very successful for DSL — consumers dislike not knowing in advance exactly how much they will have to pay. However, these models benefit operators by discouraging users who would otherwise hog bandwidth at little expense; they may also lead to lower entry-level prices [61].

Other sectors — chiefly small businesses and teleworkers — also want broadband connectivity and may be willing to pay more than $25 a month for it. They are an immediate opportunity for PLC. Western Europe has about 5 million small businesses and it is forecast that it will have about 15 million teleworkers by the end of 2005. Germany is the world's leading country market for PLC, with several trials under way. Regulations there have been quite lenient; competition is welcomed because Deutsche Telecom is an exceptionally strong telecommunications monopoly [59,64,67].

Utility companies are also trialling last-mile PLC technology in Austria, Finland, Italy, the Netherlands, Poland, Spain, Sweden and Switzerland. Spain is fast becoming a key market for PLC; the country's main utility companies, Endesa and Iberdrola, have been very active in developing the technology. Endesa has also begun a 2,500-user medium-voltage trial in the city of Zaragoza; this foreshadows the technology's evolution path [62].

3.4.2 North America

Difficulties abound for PLC in North America:

- Broadband is much more available than in Europe and household penetration is higher, at about 15 percent. Moreover, in areas where broadband is available there are usually several suppliers to choose from.
- Average end-user prices for broadband are lower than in Europe, and much less than the price of current PLC offerings. The business case for PLC for data-only use — the use that accounts for most of the mass market for broadband — is harder to make than in Europe.
- The topology of the power grid is more challenging for PLC in North America than in Europe. Each transformer serves so few end users that higher penetration is needed for a good return on investment.

North America would especially benefit from viable medium-voltage PLC solutions, whereby the number of subscribers served can be extended beyond those connected to single transformers. Many industry participants believe that such solutions are needed before the U.S. PLC market can develop. Judging by the very small number of advance trials in the United States, this is probably true. The region's poorer cable insulation makes RF interference a greater problem than in Europe. Because many PLC deployments will require medium voltage solutions, worker safety is likely to be more of an issue than in low-voltage markets [66].

However, North America also presents incentives to deploy PLC [60, 61, 64]:

- Further DSL and cable deployment faces an uphill struggle. Cable and DSL operators are limiting their new capital expenditure because of the difficult economic conditions.
- The political importance of raising broadband penetration is arguably higher than ever. The FCC has said that one of its highest priorities is to get the country broadband-enabled.
- Many places lack broadband coverage, particularly smaller communities and rural areas.
- Following the deregulation of the electricity markets in many states, electricity distributors face significant challenges in managing the demand for electricity. They are finding that, when demand exceeds expectation, the cost of buying electricity on the spot markets can be very high. PLC offers them the possibility of monitoring demand much more closely, and so may be a useful tool to increase the efficiency of electricity provisioning.

In short, offering PLC might improve the efficiency of their core business. Most PLC equipment suppliers are investigating the North American market. They plan to be there if and when the market takes off. Gartner Dataquest thinks it likely that this will not be for at least another two years. In the long term, however, North America could account for a significant part of the global PLC market.

3.4.3 Asia/Pacific And Japan

PLC penetration in Asia/Pacific and Japan is very low. However, it has great potential because major areas are not passed by copper lines. Japan only recently allowed data communications over the power grid, but already there is interest in PLC. Indeed, some of the chip vendors Gartner Dataquest interviewed said that Japan was showing the most interest [64].

3.4.4 Latin America

Low penetration of telecommunications and generally favourable distribution architectures for electricity make Latin America a market of significant promise for PLC. Moreover, although cable, wireless local loop and DSL are being deployed in key markets, the slowness of deployment and a lack of available lines have limited consumers' choice of broadband access. This potentially "opens the door" for PLC. Electricity utilities in Latin America have pursued opportunities in telecommunications, but focused on selling capacity wholesale rather than on last-mile options. With PLC, they may expand their activities to include access too.

Their established channels to the consumer may make them players to watch, both as suppliers of access infrastructure to telecommunications companies and as telecommunications competitors in their own right.

PLC trials have been under way since 2001 in Argentina, Brazil and Chile. Further trials are likely in the following years as the availability of PLC equipment grows. However, connectivity for head ends is very expensive and limited in most Latin American countries. The areas where connectivity is most plentiful are those that have deployed broadband alternatives such as DSL and cable. Despite its potential as a market for PLC, conditions in Latin America for significant short-term PLC deployment are mixed at present. Many countries— including Argentina, Colombia and Venezuela — are in economic difficulty. Others may join them. In Brazil, however, utilities have been active in the telecommunications space for years and may see opportunities to expand their role in a market that is subject to deregulation [60, 61].

3.5 REGULATIONS AND APPLICATIONS

Power line carrier communications hardware must operate within guidelines established by various statutory world standards bodies. A number of such regulatory authorities exist. In essence, the common points between the different standards covering PLC communications are [59]:

- Private-user communications must occur in the bandwidth 95-150 kHz.
- Within this bandwidth, the section from 125-140 kHz is reserved for devices that use unique addressing schemes. Such schemes avoid possible interference from neighbouring PLC devices. Outside of the "addressing band" devices are not required to use addressing schemes and interference is possible.
- PLC devices should operate at a maximum transmitted power of 500mW. This limitation is for many reasons, some chiefly being so as to avoid possible radio-frequency interference problems, and neighbouring device interference.

The standards also specify such things as network protocols, equipment impedance and methods for testing PLC devices for adherence to the regulations. Main applications of power line communication (PLC) products include: Internet access, telephony and AMR (automated meter readings). Further applications, such as home automation, home security and video conferencing may also be implemented over the same infrastructure. In the past, solutions like this for a homeowner or small business would have required several skilled technicians to install. By utilizing the electrical wiring already available, communication products allow for handling large amounts of data transmission at high speeds with no disruption to the homeowner or small business [62].

An investment in power line technology will propel the power utility companies into the broadband carrier market right next to AT&T, providing data, voice, and video transmission. The electrical utility companies will be able to provide a direct route for high-speed broadband communications directly to the home or office of their customers. Their lines are already entering every house and office building. These same companies have plenty of expertise in running and maintaining distribution cables and systems. The architecture of an electrical power distribution system is ideal for data transmission in that power is routed to the end users in a tree and branch type system.

Long distance service can be provided over the existing power transmission lines, by integrating satellite and the existing optical fibre cables that many communications companies already have in place, with the power grid. It is sure that by integration of Power line, satellite and existing fibre optic line technologies the electrical companies could challenge the local telephone companies in a few years and win. Telephone technology is not efficient or fast. It is built around large expensive central switches. Communication signals travel faster routed, than switched. Each piece of information contains its own destination or address and is routed to its final destination. The intelligence is in the data not in the system. The equipment to provide this intelligence is distributed throughout the network rather than centralized [65].

Dedicated, multipurpose communication lines make the Power line model an attractive option for the information age. Wide bandwidth and frequency division multiplexing allow for multiple lines to a single household. Ideally, an entire family could utilize their own communication devices simultaneously, whether telephone or PC, without interrupting one another.

3.5.1 Power Line As An Antenna

The electrical power distribution network is unlike other guided public telecommunications networks. The communications characteristics of the network are less controlled with large numbers of non-telecommunications devices being constantly added and removed from the network. As this wiring is not shielded, radiofrequency signals passing along it are in part, and unavoidably, radiated from it. One issue then is whether these radiated signals might interfere with radio communications. The frequent uncontrolled connection of appliances and other loads to this network means that, unlike other wire based telecommunications networks; the electrical supply network does not have well defined physical or electrical characteristics relevant to the data rates used [66].

The lack of isolation between private networks and public networks raises such questions as interference to public networks, compatibility of systems and carrier licensing requirements. The full extent of public telecommunications issues arising from widespread use of broadband power line communications systems will need further investigation.

3.5.2 Why Was HF Used In Plc?

Broadband power line communications systems typically use a number of carrier frequencies in parallel in order to spread the data over a wider range of frequencies. This allows individual carriers to be turned on or off with less impact on the overall data rate of the system. This makes the communications less vulnerable to nulls, or interference form noise or other devices connected to the network [55].

Low data rate PLC systems utilised frequencies in the range 9 kHz and 525 kHz. In this frequency range the risk of emissions is low as the attenuation of the cable is low and the wavelengths used in the signalling are long with respect to the typical cable lengths in the system. Broadband PLC systems use much higher data rates; these cannot be accommodated in the bandwidth available below 525 kHz. Instead, these systems typically use carrier frequencies in the range 2 - 30 MHz. The use of higher frequencies leads to greater attenuation of the signals along the cable. The shorter wavelengths associated with these frequencies are now more typical of cable lengths found in the network and this increases the likelihood of nulls from open circuits occurring. These effects rapidly increase with frequency, effectively limiting the use of frequencies higher than the typical values indicated above. As well, the cables are becoming more effective radiators of electromagnetic waves [55].

3.5.3 Radio Communications Issues

The main radio communications issue raised by the widespread use of broadband power line communications systems is the risk of interference to radio communications services caused by their generation of electromagnetic emissions from the power lines over which they operate. Open wire aerial power lines in particular freely radiate high frequency signals being passed along their length. There are many case histories within the records of the Australian Communications Authority (ACA) and its predecessors of signals radiated from power lines causing interference to radio communications services. The high frequency signals in these case histories have been typically generated by faults in the wired network such as arcing switch gear, coronal discharge and discharges across dirty insulators [62].

Similar experiences across the world experience have led many to believe that the deliberate placement of high frequency signals on power lines by broadband power line communications systems will lead to large scale interference problems for radio communications services particularly in the high frequency (HF) spectrum (3 to 30 MHz). Current radio communications make use of this spectrum include amateur radio, aeronautical and maritime communications and navigation services, broadcasting, fixed and land mobile operations [62].

3.5.4 Federal Communications Commission (FCC)

Power line communications systems have developed in the USA under Part 15 of the FCC Rules and Regulations, which is equivalent to Australia's class licensing regime. This part of the FCC Rules and Regulations relates to requirements for unlicensed low power radio communications devices and emissions from non-radio communications digital equipment that might otherwise cause electromagnetic interference (EMI) to radio communications services

Power line communications systems are treated in Part 15 as non-radio communications digital equipment. They are referred to in this Part as current carrier systems and specific arrangements are in place for systems operating on frequencies in the band 9 kHz to 30 MHz. The FCC Rules and Regulations specify limits for both conducted and radiated emissions for current carrier systems. Section 15.107 sets out the conducted emission limits for all Part 15 devices connected to the AC power supply, including devices used in current carrier systems. It appears that these requirements apply to the terminal devices only.

The radiated emission limits for current carrier systems [15.107(c)(3)] [15.109(e)] are the general radiated emission limits for non-specified devices that radiate either intentionally or unintentionally. The limits for conducted emissions set out in FCC Rules and Regulations section 15.107 and the limits for radiated emissions set out in section 15.109 are reproduced in **Appendix A.** These limits are significantly higher (> 100 times) than limits found in the regulation of other countries for these devices at HF frequencies.

The FCC in April 2003 [ET docket No.03-104] initiated an enquiry into current carrier systems, including broadband-over-power line systems, to obtain information on a variety of issues relating to these systems. The enquiry sought technical information and data to allow an evaluation of the current state of the technology and to determine whether changes to Part 15 are necessary to facilitate the deployment of this technology.

The closing date for comment was initially set as 7 July 2003 but was later extended to 20 August 2003 due to the large number of comments (filings) made. The period in which responses to the filings can be made is expected to close in late September 2003. The FCC initiated this enquiry as part of its statutory mandate to encourage new technologies [66].

3.5.5 Europe

The use of broadband power line communications systems in Europe is in some ways ore developed than in the USA. Last-mile systems are in use and growing in a number of European countries including Finland, Iceland, and Russia. The basic legal framework under which harmonised regulatory arrangements for these systems are being developed is that established to meet the requirements of European Economic Community EMC Directive 89/336/EEC.

3.5.5.1 European Conference Of Postal And Telecommunications Administrations (CEPT)

The European Communications Committee (ECC) of CEPT has considered in ECC Report 24 (May 2003) the compatibility between cable communications systems, including power line communications systems, and radio services. This report includes measurement results from PLT field trials held in Norway, Germany and Finland. The report also considers the compatibility of three other high data rate cable communications technologies including Digital Subscriber Line (DSL), cable TV and Local Area Network systems.

The report finds in its general conclusions that the electromagnetic spectrum below 30 MHz needs special protection and that "the risk of interference to radio services depends not only on compliance with a radiation limit but also on the different network structures and technologies as well as the frequencies used. For example, owing to the type and properties of cables installed, the structure of the network, the risk of interference caused by high frequency power line systems is much higher than with DSL or cable TV systems."

The report states that the European Commission has entrusted (Mandate 313) the European Committee for Electrotechnical Standardisation (CENELEC) and European Telecommunications Standards Institute (ETSI) with the task of developing a set of harmonised standards covering the electromagnetic compatibility (EMC) requirements for telecommunications networks using those using power lines, coaxial cables or telephone wires [61].

3.5.5.2 European Telecommunications Standards Institute (ETSI)

The ETSI Technical Committee has already produced standards for reference network architecture (TS 1010896) and coexistence (sharing) arrangements between in-house and last-mile systems (TS 101867). Other standards in development cover detailed in-house architecture and protocols. It should be noted that all of these standards are dealing with telecommunications aspects and that none directly address potential interference issues for radio communications systems.

The Technical Committee is working through CENELEC with the International Electrotechnical Committee specialist body CISPR (the International Special Committee on Radio Interference), on EMC issues related to power line systems. The CISPR standard for information technology equipment conducted limits at mains terminals and telecommunications ports (CISPR 22), together with its European counterpart EN 55022, are in the process of being updated to include changes clarifying their application to power line systems [57].

Currently, several European countries have adopted their own requirements for power line communications systems. These include: Germany, where limits for emissions from all cable systems are set out in NB308; and the United Kingdom - covered by MPT 1570, which has been recently updated. There is also a limit proposed by Norway. See **Appendix C** for a comparison of these limits, as taken from ECC Report 24.

In summary, the European Communications Committee has identified a significant risk of interference to HF radio communications services (ECC Report 24). Based on these findings, Europe is currently developing a range of telecommunications and other harmonised standards specifically covering broadband power line communications systems. There is, however, a growing number of systems already being deployed in Europe and surrounding countries to provide last-mile broadband services using devices compliant with EN 55022.

3.5.6 International Electrotechnical Commission (IEC)

The IEC is the leading global organisation that prepares and publishes international standards for all electrical, electronic and related technologies. Work related to broadband power line communications systems is currently being undertaken by the IEC

International Special Committee on Radio Interference (CISPR).

3.5.7 International Special Committee On Radio Interference (CISPR)

CISPR has developed a range of EMC standards for electronic equipment that have been widely adopted by regulatory authorities around the world, including Australia. CISPR Standard 22 on the limits and measurements of emissions from information technology equipment is currently in the process of being updated. The CISPR 22 work program includes a project to provide clarification of the application of CISPR 22 to PLC equipment (project number: CISPR 22 Amd.2 f9 Ed.3). This work was scheduled for completion in August 2003; however, due to the level of debate regarding the impact on radio communications services from power line systems the work is still incomplete [59, 62].

The debate is centred on the appropriateness of the conducted signal measurement methods and limits in CISPR 22 which are intended to limit the amount of radiofrequency energy finding its way from information technology equipment onto mains power networks. The radiated signal limits and measurements methods would only be applicable to the cases of power line communications terminal devices and radiation from the case of these terminal devices does not present a significant interference risk [62].

CHAPTER FOUR

CHARACTERISTICS AND IMPAIRMENTS OF POWER LINE CHANNEL

4.1 OVERVIEW OF THE POWER LINE CHANNEL

Evaluation of any communication technology is only relevant in the context of the operating environment. This seemingly obvious point, frequently bypassed in textbook analysis, can not be overlooked in the field of power line communication. We begin by examining the three common assumptions which must be modified in order to be applicable to power line analysis. The majority of engineering texts rely heavily on the principle of superposition. Unfortunately, the conditions required for superposition to be applicable (i.e. linearity and time invariance) are not met for the majority of power line networks. One cause of non-linearity is when a packet's signal voltage adds to the AC line voltage and causes power supply diodes to turn on and off at the packet carrier frequency. A common example of time variance is when the impedance at a point of a power line network varies with time as appliances on the network are alternately drawing and then not drawing power from the network at twice the AC line frequency.

Most in the industry agree that useful data rates for consumer home networking start around 1 M bits/second. At that data rate, the power line provides an inhospitable communications channel. With multiple outlets in every room though, the payback in consumer convenience is obvious. The power line as a communications channel has specific characteristics that must be considered. These include the dominant and widely varying noise sources, impedance changes, and multipath effects [3]. Noise sources are electronic, electro-mechanical, and even induced by the power lines themselves. Some noise is harmonically related to the 50 or 60 Hz power. Light dimmers and related products that use triacs create impulse noise on every cycle or half cycle of power. Some power supplies, especially poorly designed switching supplies, conduct quite a bit of noise onto the power line. This noise may have high harmonic content related to the switching frequency of the supply. One of the worst offenders is the brush motor with its rotating spark-gap generators that create broadband noise. Intellon (a broadband telecommunication company) has even noted cases where corroded junctions in the building wiring have a semiconductor effect whose nonlinearity induces noise on every power half cycle [23]. Even if every device were unplugged, there would still be noise present, coupled onto the power line from outside RF sources.

These noise sources have both time domain and frequency domain characteristics. The easiest way to get a first order understanding of Signal to Noise Ratio (SNR) on the power line is to look at noise amplitude as a function of frequency, as shown in Figure 4.1. This plot shows the maximum noise level recorded for a particular test site as a function of frequency. The maximum noise level is indicative of the amount of noise energy the communications signal will be competing against at particular instances in time, but not on a continuous basis. The average noise level is 20 to 30 dB less than this maximum recorded value, which is more indicative of the potential for communicating over this channel [23].

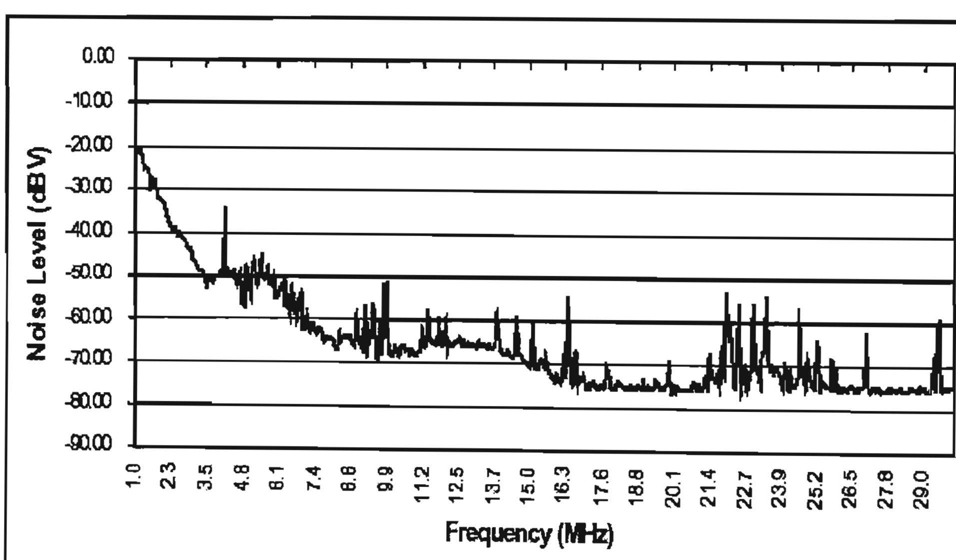

Figure 4.1: Maximum Noise Level (Source: Intellon Corp [17])

The other half of understanding the power line channel is in what happens to the desired communications signal as it leaves the transmitter and travels to the receiver. Power line does not present a controlled impedance to the transmitter. Devices plugged into the line primarily determine the impedance. Some devices even modulate the impedance, making it impossible to source a controlled amplitude signal. Finally, power line has its own multipath effects just like an RF channel. Multipath causes selective fading and intersymbol interference. Both of these effects vary with time and outlet location. The plot in Figure 4.2 is an example of measured attenuation between random outlet pairs in many homes. On average, the band of interest presents an attenuation level that is tolerable. But the nulls can be deep (up to 80 dB) and are unpredictably located. The random nature of these deep notches is what makes picking the "perfect" power line modulation frequency nearly impossible. Single carrier narrowband modulation relies on chance that the null will not overlap the carrier or uses equalization in an attempt to overcome the channel variation [14, 23]. The equalizer quickly becomes too complex to build cheaply and simply cannot recover from a "dead short" in band.

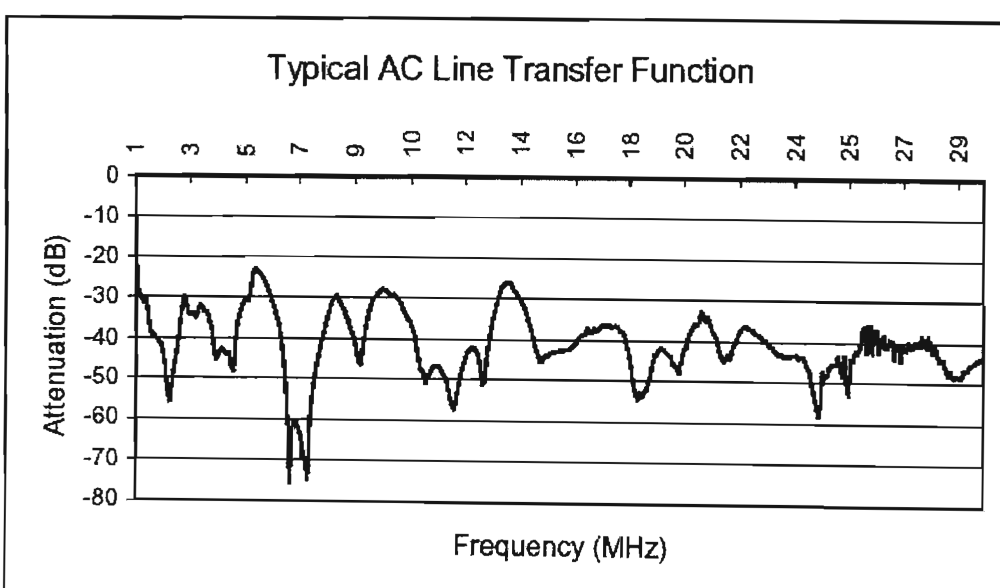

Figure 4.2: Outlet to Outlet Attenuation Level (Source: Intellon Corp [17,23])

4.2 CHANNEL CHARACTERISTICS

Power lines constitute a rather hostile medium for data transmission. Varying impedance, considerable noise, and high attenuation are the main issues. The channel mixes the nasty behaviour of a power line with that of a communication channel. The transmission environment for PLC seems much worse than that for mobile communications, so we need to not only utilize existing advanced technologies, but also create novel ones.

Channel characteristics can be both time- and frequency-dependent, and also dependent on the location of transmitter and receiver in the specific power line infrastructure. Hence, the channel can in general be described as random time varying with a frequency-dependent signal-to-noise ratio (SNR) over the communication bandwidth. Generally, a measured in-house (10 m) transfer function shows some deep narrowband notches spread over the whole frequency range.

To understand the channel response and the impedance behaviour, Electronics Workbench (EWB) and Matlab 6.1 programme were used to simulate the transmission line. EWB includes a T-line model in which you set various per-unit-length parameters of the line. The transmission line module included in Matlab 6.1 and Electronics Workbench was set to have the parameters of common 12-gauge copper wiring, which were calculated as in Table 4.1:

Parameter	Formula	Variables	Variable Value	Parameter Value
Inductance	$L = 4\pi\times10^{-7}\ln(D/r')$	D = distance between wires r' = 0.7788 × radius of conductor	D = 0.635 cm r' = 0.08 cm	L = 2.60 μH / m
Capacitance	$C = \pi\varepsilon / \ln(D/r)$	D = distance between wires r = radius of conductor	D = 0.635 cm r = 0.103 cm	C = 45.8 pF /m
Resistance	$R = \rho$	ρ = Resistance per unit length	ρ = 5.21 mΩ / m	R = 5.21 mΩ / m

Table 4.1: Transmission line model (Source: Telkom SA)

The per-unit conductance of the line's insulation was in the microsiemen-per-meter range and was therefore ignored.

4.2.1 Channel Impedance

Quite a few measurements in the frequency and time domains for high-bit-rate transmission have been reported, converging essentially to some general conclusions. Impedance is highly varying with frequency and ranges between a few ohms and a few kilo-ohms with peaks at some frequencies where the network behaves like a parallel resonant circuit. In most frequency ranges the impedance shows inductive or capacitive behaviour around 90 Ω to 100Ω. The net impedance is strongly influenced by the network topology and connected loads, so we can say that the low voltage mains do not have essentially characteristic impedance since loads being switched on and off randomly introduce a change in impedance [3].

Measurements in houses for frequencies of 5-30 MHz resulted in some general and common conclusions for the absolute value $|Z|$ of the impedance:

- The magnitude $|Z|$ increases with frequency in the range of 5-20 MHz.
- It shows strong fluctuation between a maximum and a minimum value.
- Its mean value increases from about 5 Ω at 20 kHz to about 120 Ω at 30 MHz
- There are no big differences between the mean values of impedance presented throughout the 30 kHz to 1 MHz spectrum range, whereas throughout 1-30 MHz they are almost uniform
- Mostly impedance values do not vary significantly from country to country.
- Resonances can occur in residential networks, usually above 40 kHz. They make the impedance at higher frequencies more unpredictable than that at the frequency range of 5-20 kHz.
- Of various loads, resistive heating loads cause the greatest residential impedance changes for lower frequencies.

Carrying out impedance measurements outside buildings from 9 to 95 kHz, we find that the residential power circuit has extremely low impedance in most cases. The impedance varies with time and location. A maximum value that was measured was 4 Ω at 9 kHz at the rural location, and a minimum value was 0.4 Ω at 40 kHz at the suburban location. These low values are attributed to "the large capacitor that is used for power factor correction at 50 Hz that represents a short circuit in 9 to 95 kHz range reducing even lower overall impedance values"

Characteristic indoor and outdoor records of *attenuation* have been reported in many literatures. Measurements have been made at a voltage of 0.35 V rms on in-house lines, resulting in about 15 dB attenuation, and on a 1 km cable feeding a cluster of houses, resulting in 50 dB attenuation. In the range of frequency of 9-95 kHz the line losses ranged between 40-100 dB/km depending on the location where the attenuation was measured. So far research has focused on LVEDNs (Low Voltage Electricity Distribution Network), but some studies on medium voltage cables (11-32kV) are still being investigated. A large variety of cables exist differing in general structure, number of cores, conductor material, and insulation used.

Another area of confusion arises from the common view that wiring capacitance dominates signal propagation effects. This simplified view is rooted in assumptions which do not accurately reflect power wiring environments. While it is true that wire capacitance is dominant for cases where the termination or load impedance is much greater than the characteristic impedance of the wire, power lines are frequently loaded with impedances significantly below the characteristic impedance of the wire [53]. Common examples of loads which present a low network impedance at communication frequencies include capacitors used within computers and television sets to meet electromagnetic emission regulations and resistive heating elements found in cooking ovens, space heaters and the like. The impedance of these devices is typically an order of magnitude, or more, below the characteristic impedance of power wiring. This can be seen quantitatively by comparing the entries in Table 4.2 and Table 4.3.

Wire Type	Zo ohms	C/m (pF)	L/m (uH)	R/m (ohm) @130kHz	v (m/ns)
12-2 BX metal clad	74.2	74.48	0.427	0.0433	0.181
12-2G Romex NM-B	143	34.12	0.702	0.0446	0.204
18-2 Lamp cord	124	43.31	0.666	0.0771	0.186
18-3 IEC power cord	79.6	101.05	0.640	0.1033	0.124

Table 4.2: Power line wire characteristics (Echelon Corp [53])

Low impedance Load	Impedance at 100 kHz
0.1 uF EMC capacitor	16 ohms
2 kW 240VAC Space Heater	30 ohms

Table 4.3: Low impedance power line loads (Echelon Corp [53])

While a full transmission line model, complete with high frequency models of each load, is required to fully characterize power line attenuation, there is one simplification which can be used as a first order approximation. For cases where wire runs are less than 1/8 of a wavelength (approximately 250 meters at 100 kHz) and communication is confined to a single power phase, the presence of low impedance loads causes wire inductance to dominate [53]. In many instances a lumped model which includes only wire inductance and low impedance loads closely approximates actual signal attenuation. Frequently the only other effect which must be considered in order to match measured values is the loss encountered when the communication signal must cross power phases. This loss, typically in the range of 5 to 25dB, is influenced by a number of variables including distribution transformer coupling, distribution wire cross-coupling, multi-phase load impedance and circuits which are explicitly installed to reduce this loss. Combining the above effects we find that 96% of the time the attenuation within a single residence falls in the range of 54dB near 100 kHz.

4.3 CHANNEL TRANSFER FUNCTION

Using the power distribution grid for communication purposes the transmission line is appropriately described by a linear, dispersive, time–invariant system, at least for time intervals which are very long compared to the duration of one Orthogonal Frequency Division Multiplexing symbol (OFDM–symbol). Thus, the channel is characterized by a channel transfer function $H(f)$ and a subsequent additive noise term. Throughout this chapter, $H(f)$ constitutes the transfer function in the equivalent low–pass domain.

Due to the structure of typical power line networks with a lot of impedance discontinuities a transmitted signal will be received as a number of distinctively delayed and attenuated signals at the receiver side corresponding to reflections from those discontinuities. Hence, a multi–path signal propagation model seems to be suitable to describe the channel transfer characteristics. Neglecting the (slow) time–variance of the channel, this was used for presenting a deterministic expression of $H(f)$ depending on some parameters [26, 27].

But in many situations, a stochastic model regarding the transfer function as a random process $H(\eta, f)$, where η denotes the atomic event of the random experiment, is desirable instead of one determined transfer function. Clearly, as the signal attenuation and phase on the long term increase with the frequency f, $H(\eta, f)$ is a *non–stationary* random process along the frequency axis. Sample functions of this process are illustrated in Figure 4.3.

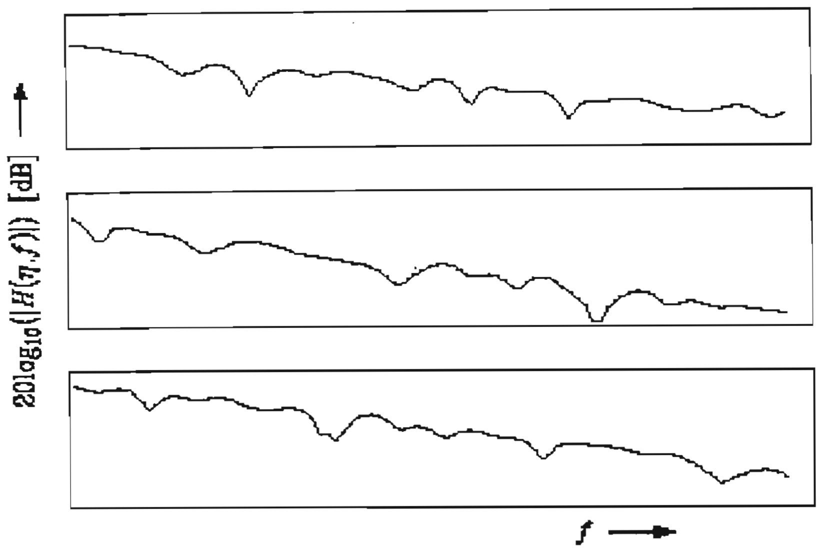

Figure 4.3: Sample functions of the non–stationary random process $H(\eta, f)$

For a certain frequency f the random variable $H(\eta, f)$ results from the superposition of numerous independent random variables which represent the effects of mismatched lines in power line networks. Therefore, the application of the central limit theorem is motivated, which yields $H(\eta, f)$ to be a complex *non–stationary Gaussian process* with autocorrelation function (* denotes complex conjugate and ε denotes expectation) [29].

$$\phi_{HH}(f_1, f_2) \cong \varepsilon\{H(\eta, f_1) * H^*(\eta, f_2)\} \qquad (1)$$

and mean value

$$m(f) \cong \varepsilon\{H(\eta, f)\} \qquad (2)$$

The second moment of the non–stationary process, i.e., the average power of the transfer function, will be denote by

$$P(f) \cong \phi_{HH}(f, f) = \varepsilon\{|H(\eta, f)|^2\} \qquad (3)$$

Generally, the average gain $\sqrt{P(f)}$ and the frequency dependent average phase term $\varphi_0(f)$ of the set of transfer functions can be assumed to be characteristic for different types of power line networks and communication links over these networks. The average power transfer function may be approximated by

$$P(f) \propto \text{Exp } (-a \cdot f) \tag{4}$$

In many situations, where the attenuation parameter a corresponds to different network types, the average phase term can be expressed by

$$\varphi_0(f) = \sum_i c_i f^{b_i} \tag{5}$$

where c_i are normalization constants, and, for example, terms for b_i=0 correspond to the phase term due to the transformation into the low pass domain, terms for b_i=0.5 describe the skin–effect, and terms for b_i=1 give the phase term representing the average signal delay. Hence, it is convenient to eliminate these average values and to define a normalized random process

$$\tilde{H}(\eta, f) \cong \frac{H(\eta, f)}{\sqrt{P(f)} \cdot e^{-j\varphi_0(f)}} \tag{6}$$

For simplicity, let the mean value of $\tilde{H}(\eta, f)$ be constant over f. If additionally the autocorrelation function (acf) $\phi_{\tilde{H}\tilde{H}}(f + \Delta f, f)$ of this normalized process only depends on the frequency difference Δf, i.e., $\phi_{\tilde{H}\tilde{H}}(f + \Delta f, f) \cong \phi_{\tilde{H}\tilde{H}}(\Delta f), \forall f \in \Re$. $\tilde{H}(\eta, f)$ is well modelled by a *stationary Gaussian process*.

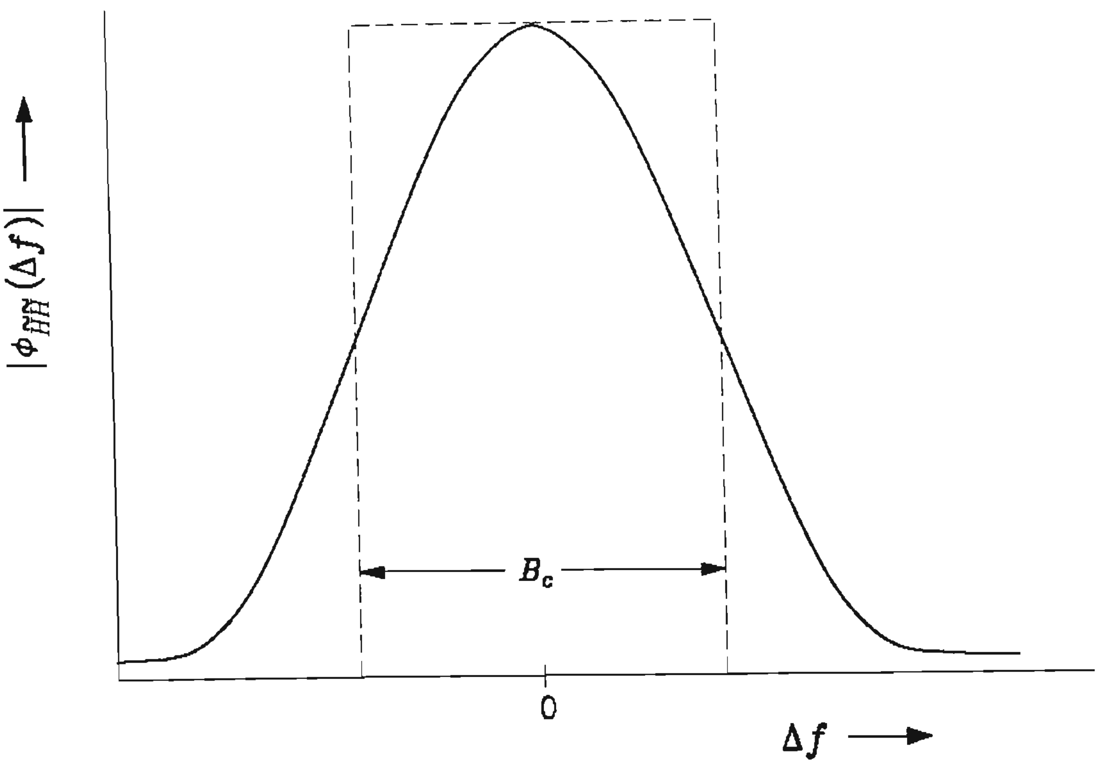

Figure 4.4: Example of the autocorrelation function

An exemplary acf $\phi_{\tilde{H}\tilde{H}}(\Delta f)$ for this normalized stationary process is depicted in Figure 4.4. Within the coherence bandwidth B_c which is defined by

$$B_c = \frac{1}{\phi_{\tilde{H}\tilde{H}}(0)} \int_{-\infty}^{\infty} \phi_{\tilde{H}\tilde{H}}(f) df \qquad (7)$$

the transfer function does not change significantly.

4.4 CHANNEL NOISE

Communication signals at low frequency are propagated along the low voltage power line through conducted emission with very little energy radiated from the line causing interference to other communication services. Different noise sources, motors, radio signals, and power supplies result in a noise curve very much dependent on location and time. Generally, channel noise varies strongly with frequency, load, time of day, and geographical location.

The noise spectrum in the frequency range up to 145 kHz consists of four types of noise:

- Coloured background noise, which is the summation of low power sources like universal motors. Its power spectral density is frequency-dependent and decreases for increasing frequencies.
- Periodic impulse noise (synchronous and asynchronous to the power frequency) stemming from appliances that produce harmonies of 50 or 100 Hz.
- Narrowband noise consisting of sinusoidal signals with modulated amplitudes (radio stations, the horizontal retrace frequency for television, etc.).
- Asynchronous impulsive noise (noise bursts of switching operations).

The noise power level ranges according to the distance between the noise source and receiver, and in most cases was found to be below -40 dB (W/kHz). Significant noise sources are universal motors to frequencies up to 50 kHz. It is worth mentioning that, since noises as well as wanted signals are subject to attenuation, noise sources close to the receiver will have the greatest effect on the received noise structure, particularly when the network attenuation is large [53].

If attenuation were the only impairment, then receiver gain could simply compensate for this signal loss. Both the noise and distortion characteristics of the power line must also be considered before we have a picture of the operating environment which is adequate for use in technology comparison.

Many electrical devices which are connected to the power mains inject significant noise back onto network. The characteristic of the noise from these devices varies widely. Examination of the noise from a wide range of devices leads to the observation that the noise can also be classified the following categories:

- High frequency Impulse noise (at twice the AC line frequency)
- Tonal noise
- Impulse noise

4.4.1 Impulse Noise

The most common impulse noise sources are triac-controlled light dimmers. These devices introduce noise as they connect the lamp to the AC line part way through each half AC cycle. When the lamp is set to medium brightness the inrush current is at a maximum and impulses of several tens of volts are imposed on the power network. These impulses occur at twice the AC line frequency as this process is repeated in every 1/2 AC cycle. Figure 4.5 shows an example of this kind of noise after the a high pass filter has removed the AC power distribution frequency

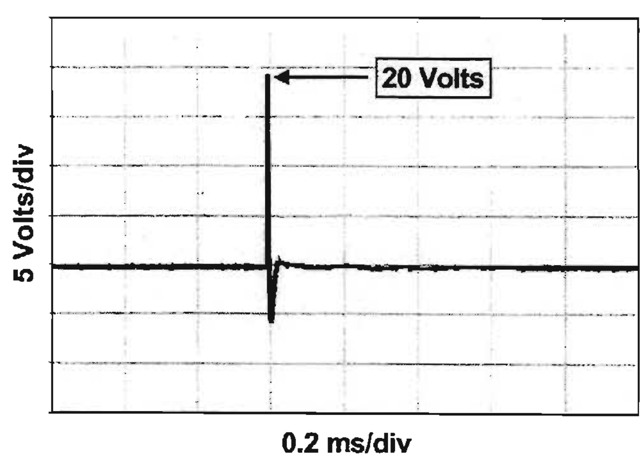

Figure 4.5: Lamp dimmer impulse noise (Source: Echelon Corp [53])

4.4.2 Tonal Noise

It is often useful to divide tonal noise into the two sub-categories of unintended and intended interference. The most common sources of unintended tonal noise are switching power supplies. These supplies are present in numerous electronic devices such as personal computers and electronic fluorescent ballasts. The fundamental frequency of these supplies may be anywhere in the range from 20 kHz to >1 MHz. The noise that these devices inject back onto the power mains is typically rich in harmonics of the switching frequency [53]. Noise from the charging stand of an electronic toothbrush is shown in the plot of Figure 4.6. Note the similarity between the switching supply noise and an ideal sawtooth waveform.

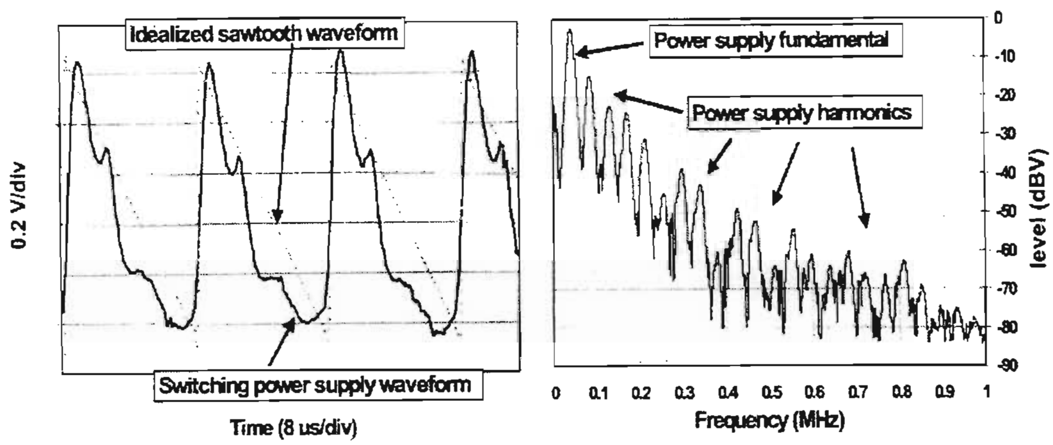

Figure 4.6: Noise from an electronic toothbrush charging stand (Source: Echelon Corp [53])

Intentional tonal noise can result from devices such as power line intercoms and baby monitors. In the United States and Japan these devices generally operate at frequencies between 150 kHz to 400 kHz; injecting signals of several volts peak to peak onto the power line. A second source of intentional tonal noise results from pickup of commercial radio broadcasts. Power wiring acts an antenna to pick up signals from these multi-thousand watt transmitters. Interference on the order of a volt peak-to-peak at frequencies just above the communication band is not uncommon. Note that this interference has very specific implications for the filtering requirements of any power line transceiver

3.4.3 High Frequency Impulse Noise

High frequency impulse noise finds its source in a variety of series-wound AC motors. This type of motor is found in devices such as vacuum cleaners, electric shavers and many common kitchen appliances. Commutator arcing from these motors produces impulses at repetition rates in the several kilohertz range.

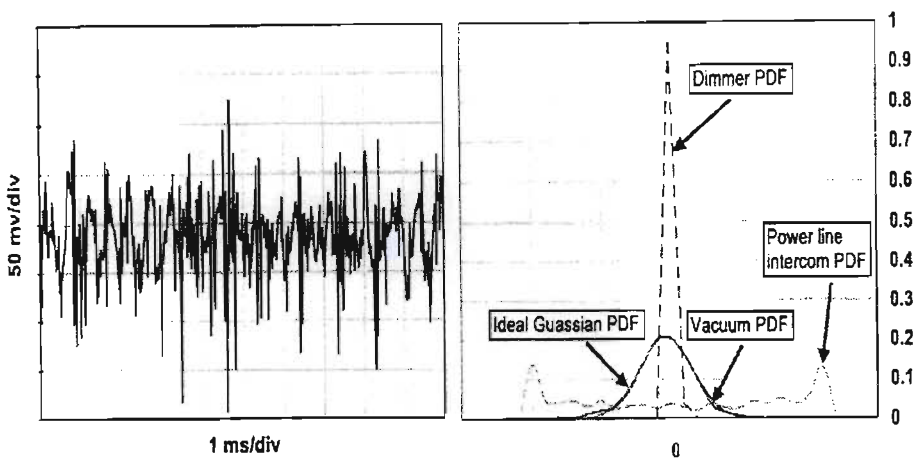

Figure 4.7: Vacuum cleaner noise and amplitude distribution for common impairments (Source: Echelon Corp [53])

Figure 4.7 is an oscilloscope plot of noise from a household vacuum cleaner on the left and on the right amplitude distribution plots of three common types of impairments. An ideal Gaussian distribution fitted to the vacuum distribution is also shown.

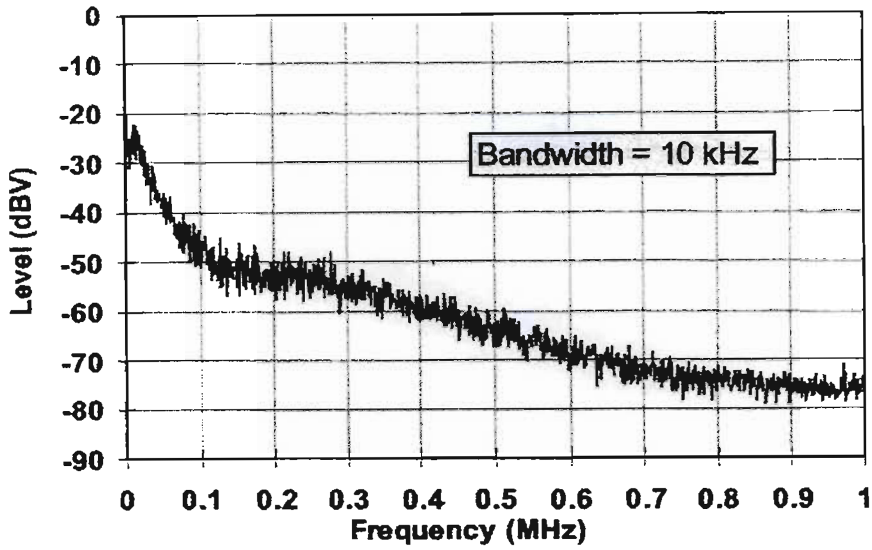

Figure 4.8: Vacuum cleaner noise spectrum (Source: Intellon Corp [17,23])

Figure 4.8 is a frequency domain view of the noise from the same vacuum cleaner showing the wide band spectrum on the left and a close up of the part of the spectrum typically used for power line communications on the right. Note that, of the various categories of power line noise, this motor noise is the only type which bears even a remote resemblance to white Gaussian noise commonly used to analyze many communication systems.

As mentioned earlier a complete analysis of power line characteristics must include an analysis of the distortion characteristics of the channel. Various reactive loads and wire characteristics combine to create a channel with highly distorted (and time varying) frequency response. Figure 4.9 illustrates this point showing the magnitude and phase characteristics between two points of a sample power line network.

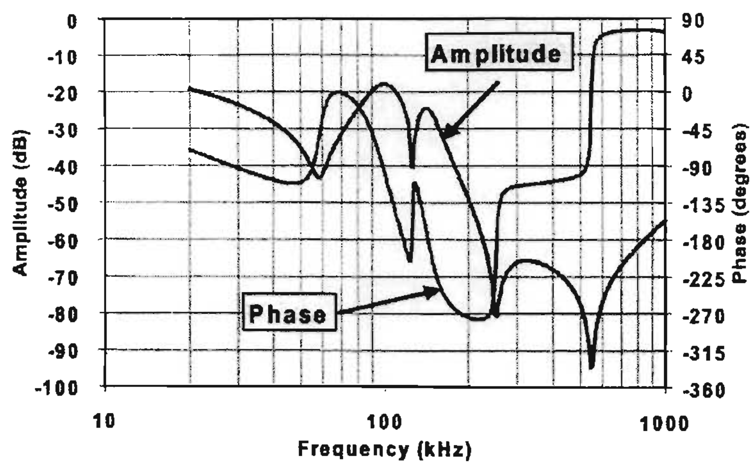

Figure 4.9: Example of power line frequency distortion (Source: Cogency [9,22])

Having reviewed the characteristics of the power line, we are now in the position to compare various communication technologies within the context of their true operating environment. This will be covered in the next chapter.

CHAPTER FIVE

OFDM AS A MODULATION SCHEME FOR POWER LINE COMMUNICATION

5.1 COMMUNICATION TECHNOLOGIES

We will begin by examining the three technologies in the order of historical significance. Many early power line communication devices used narrow band transmission combined with a phase-locked-loop type receiver. Three variations of narrow band transmission are illustrated in Figure 5.1. For clarity these figures do not include wave shaping which is typically applied to remove abrupt transitions.

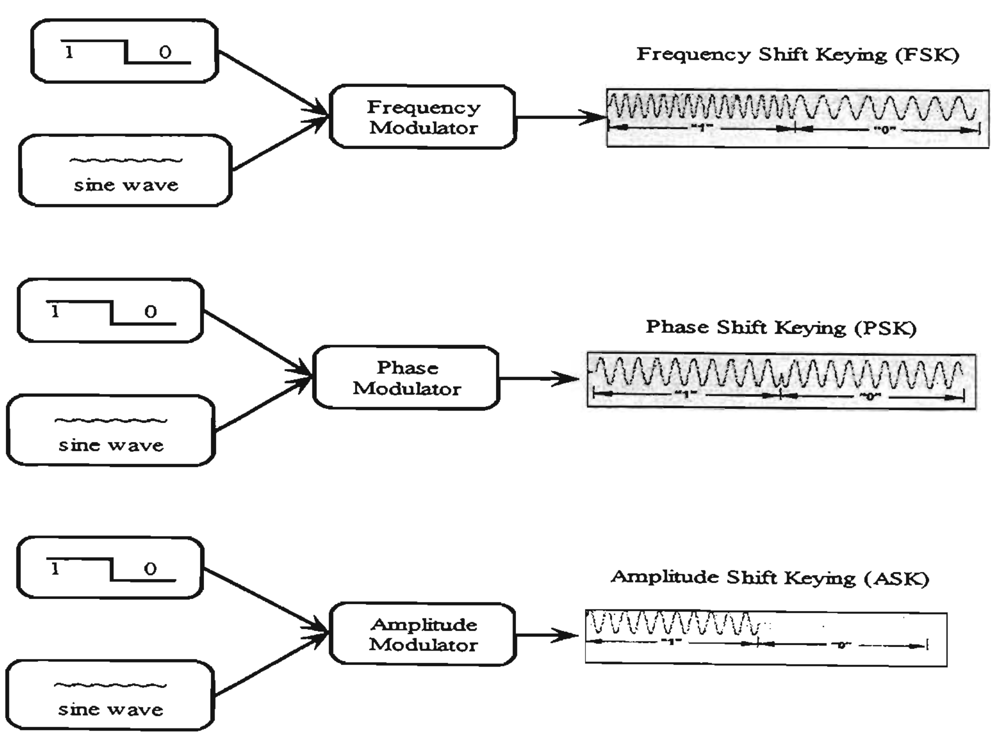

Figure 5.1: Methods of narrow band modulation

A phase-locked-loop receiver which can be used to receive any of these three transmissions is illustrated in Figure 5.2. With this technology the PLL typically adjusts the phase of the receiver's local oscillator until the down converted and filtered signal in the quadrature (Q) channel is nulled out. The filtered 'I' channel signal is then used as a recovered representation of the transmitted data.

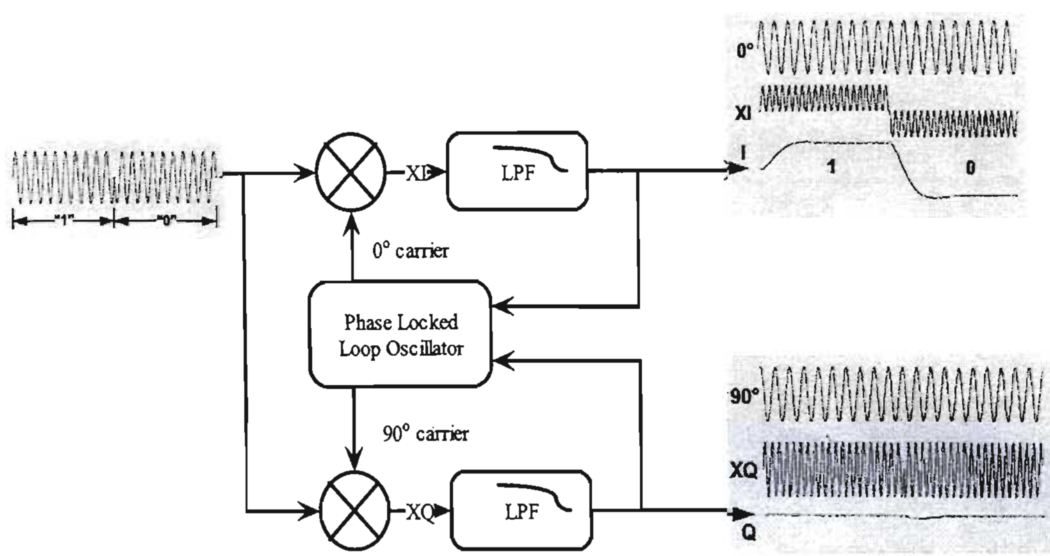

Figure 5.2: A phase locked loop receiver

A serious limitation with this approach emerges when it is evaluated in light of typical power line noise. Impulse noise from light dimmers is spread over several bit times by the required narrow receive filter. Figure 5.3 is an oscilloscope plot of the output from one of these receivers with a 66dB attenuated input signal - disturbed by an impulse from a light dimmer located next to the receiver. As the graph shows, two of the received bits are in error. This and other limitations have caused many companies to abandon this technology for use in power line communication [53].

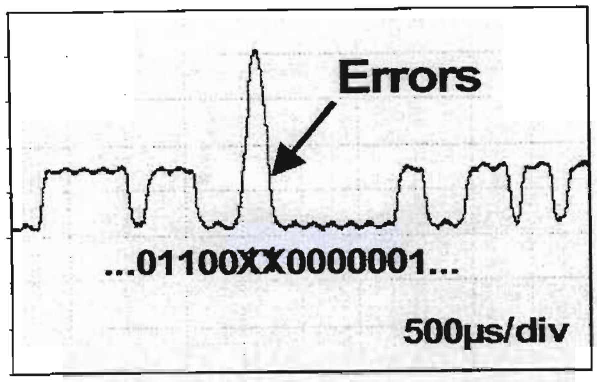

Figure 5.3: Error in PLL recovered signal due to impulse noise (Source: Spectrum [3,72])

5.2 MULTICARRIER MODULATION

Orthogonal Frequency Division Multiplexing is a spectrum efficient modulation technique that enables wireless transmission at very high data rates. Data rates in excess of 100 Million bits per second (Mbps) are possible. Enhanced OFDM is a multiple carrier system with characteristics that make it adaptable to environments with harsh multi-path reflections, large narrowband interference, and impulse noise without equalization. Equalization becomes very complex and expensive, if not impossible, for data rates above 10 Mbps with single carrier modulation. The problems caused by multi-path reflections increase with distance and data rate. The decision to select OFDM was largely due to OFDM's ability to mitigate multi-path reflections while making efficient use of the available spectrum.

OFDM modulation is essentially the simultaneous transmission of a large number of narrow band carriers, sometimes called sub carriers, each modulated with a low data rate, but the sum total yielding a very high data rate. The history of OFDM dates back to 1966, when R. W. Chang published his paper on the synthesis of band-limited orthogonal signals for multichannel transmission (Bell System Technical Journal). A major contribution to OFDM was later presented in 1971 by S. B. Weinstein and P. M. Ebert, who used the discrete Fourier transform (DFT) to perform baseband modulation and demodulation. They also added a guard space between OFDM symbols to combat intersymbol interference (ISI) caused by multi-path reflections. In 1980, A. Peled and A. Ruiz introduced the cyclic prefix in the guard space to solve a final problem with maintaining orthogonality, a lack of which causes interchannel interference (ICI). With today's technology, the DFT processor and other circuitry required to implement OFDM, can be built in a very low cost CMOS IC. Very high-speed, low cost consumer transceivers can now be a reality [17].

5.2.1 Theory Of Operation

The basic idea of OFDM is to divide the available spectrum into many narrowband, low data rate carriers (or sub carriers). To obtain high spectral efficiency the frequency response of the sub carriers are overlapping and orthogonal, hence the name OFDM. Each narrowband sub carrier can be modulated using various modulation formats where BPSK, QPSK and QAM (or the differential equivalents) are commonly used.

Since the modulation rate on each sub carrier is very low, each sub carrier experiences flat fading in a multi-path environment and is easy to equalize. The need for equalization can be eliminated by using differential QPSK (DQPSK) modulation where the data is encoded as the difference in phase between the present and previous symbol in time on the same sub carrier (see Figure 5.4). Differential modulation improves performance in environments where rapid changes in phase are possible.

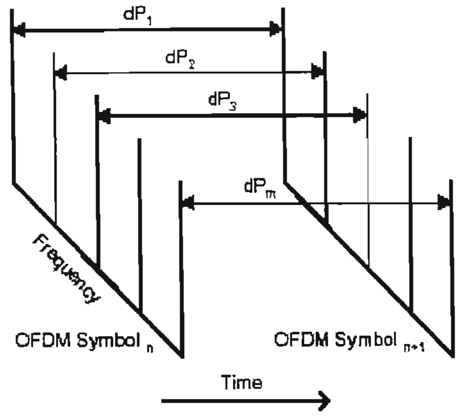

Figure 5.4: Differential phase encoding across symbols (Source: Intellon Corp [17,23]).

Enhanced OFDM can be implemented equally well, with coherent (non-differential) modulation and demodulation to maximize the signal to noise ratio of the system, while achieving the greatest possible range [14, 17,23]. Such a system is illustrated in Figure 5.5. This approach is preferred for performance oriented systems, like point to multi-point licensed radios, where the highest bit rate per Hertz is most important.

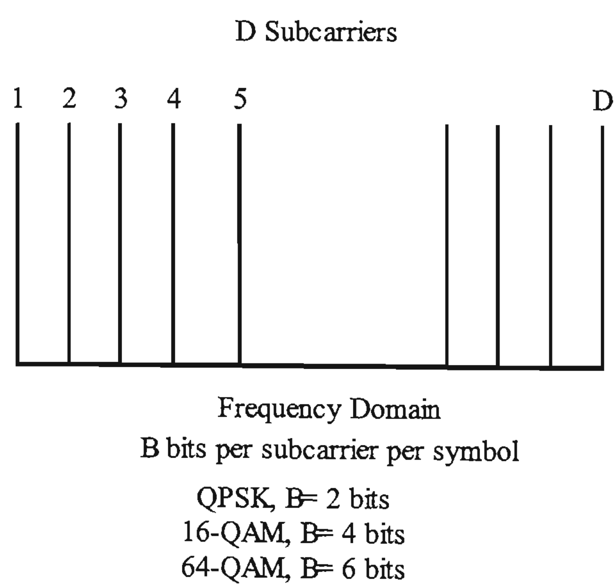

Figure 5.5: OFDM using coherent modulation on sub carriers (Source: Intellon Corp [17,23]).

5.2.2 Transmitter

OFDM modulation is generated using a fast Fourier transform (FFT) processor. M bits of data are encoded in the frequency domain onto D sub-carriers as shown in Figure 5.5. M = D x B where B = the number of bits per modulation symbol. B=2 in the case of QPSK or DQPSK. An inverse FFT (IFFT) is performed on the set of frequency sub carriers, converting to the time domain (see Figure 5.6) and producing a single enhanced OFDM "symbol". The length of time for the OFDM symbol is equal to the reciprocal of the sub carrier spacing and is generally a very long time compared to the data rate [17].

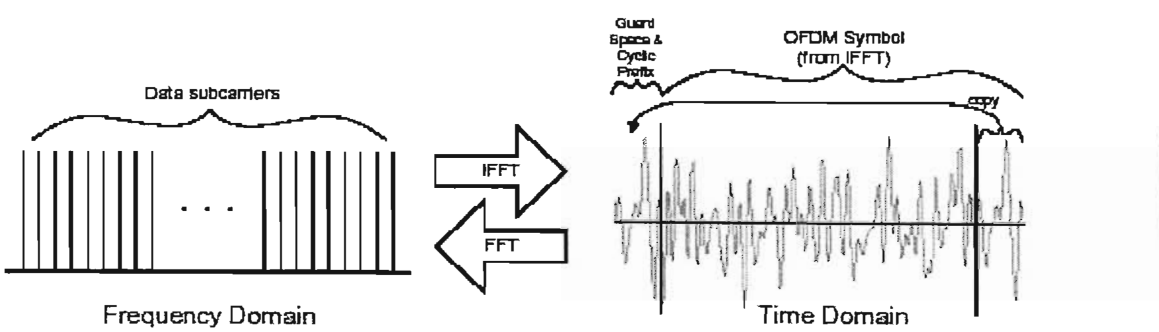

Figure 5.6: Transform from the frequency to the time domain and adding the cyclic prefix (Source: Intellon Corp [17,23]).

5.2.3 Receiver

OFDM signals are demodulated by the reverse process of the transmitter (see Figure 5.6), where the cyclic prefix is removed from the time domain signal, and an FFT is performed on each symbol to convert to the frequency domain. Data is decoded (in the case of DQPSK) by examining the phase difference of sub carriers between adjacent OFDM symbols. Additional requirements for the receiver are frequency and time synchronization [17]. Phase synchronization of the local oscillators is not required with differential modulation.

5.2.4 Multi-Path

A cyclic prefix is added to the enhanced OFDM symbol to maintain complete orthogonality in a time-dispersive channel (caused by multi-path reflections). This prefix copies the last part of the symbol and adds the copy to the beginning of the symbol (see Figure 5.6). The long enhanced OFDM symbol time, generally many microseconds, combined with the cyclic prefix, which is usually a small percentage of the enhanced OFDM symbol time, are key factors that enable performance in a time-dispersive channel.

Conventional modulation suffers from interference caused by time-delayed reflections of the original signal overlapping successive symbols, or ISI. Consider the transmission of conventional QPSK symbols at a rate of 1 MHz (yielding 2 Mbps) in a time-dispersive channel with reflections delayed as much as 1 microsecond [23]. These reflections of 1 microsecond occur in indoor environments with several hundred feet of range. In this example, the symbol time is 1/(1 MHz) = 1 microsecond. When multiple copies of the original signal are delayed up to 1 microsecond in arriving at the receiver, the symbol being decoded (likely to be the signal from the most direct path) is interfered with, and corrupted by, the delayed signals.

These delayed signals contain the previous symbol transmitted 1 us earlier. This distortion can be corrected with equalization, but becomes much more difficult when the symbol rate is increased to 10 MHz. For example; potentially all 10 preceding symbols interfere with the symbol currently being decoded. With OFDM, many hundreds of bits (see above: D x B) are transmitted for each symbol making the duration of the symbol many microseconds long [14,17].

Selecting a cyclic prefix of 1 microsecond for the example above, all received copies of the original signal would contain the same enhanced OFDM symbol (except shifted in time) and there would be no ISI. For long distance transmissions, such as the DVB standard where the distance may be 50 miles or more, the time-dispersion is many microseconds longer. In this case, the enhanced OFDM symbol time is specified to be hundreds of microseconds and the cyclic prefix many microseconds, in order to combat interference from reflections. Due to the properties of OFDM, the stochastic process along the frequency axis is transformed into an equivalent *discrete–time process*, which models a *fading* channel.

5.3 APPLICATION OF OFDM TO POWER LINES

Core of the OFDM–system is the conversion of the convolution of the transmit signal and the channel impulse response into a component-wise multiplication of samples of their Fourier transforms. For transformation of linear convolution into cyclic convolution, each block of D channel symbols is preceded by the D_0 last symbols of the same block at the transmitter and at the receiver only D symbols out of $D+D_0$ received symbols is taken. D_0 is commonly referred to as guard interval [18, 25]. If the guard interval is at least as long as the (discrete–time) channel impulse response, OFDM partitions the dispersive channel into D independent AWGN–sub channels (sub carriers). The sub channel transfer factors λ_v are samples of the channel transfer function $H(f)$:

$$\lambda_v = H(\Delta f \cdot v), \quad v = 0,1,....,D-1. \tag{8}$$

where Δf denotes the OFDM–sub carrier spacing. Generally, the signal–to–noise ratios in these sub channels differ significantly. Clearly, if the sub channel SNR is known at the transmitter side the transmit power and information rate can be appropriately assigned (loaded) to each sub channel. In power line communication schemes channel state information usually is not available at the transmitter, especially for the point–to–multipoint transmission situations. Thus, loading is not further considered [30, 31].

Without loading, equal power and equal information rate have to be assigned to the OFDM–sub carriers. If the signal processing is performed independently in each sub channel, only a subset of sub carriers would allow reliable communication. An advantageous alternative is to employ channel coding across the sub carriers [32]. In this case, in the decoding the reliably received symbols from a sub channel with relatively high SNR are used to restore the unreliable symbols from a sub channel with relatively low SNR.

5.3.1 Fading Channel Model

First, we regard the transmission of only one OFDM– symbol. The signalling along the discrete frequency axis in OFDM is equivalent to transmission over a frequency non–selective (flat) discrete–"time" fading channel. Describing this fading channel in the equivalent low–pass domain, the complex valued channel state is related to the sub carrier transfer factors and the channel transfer function, respectively, by ($k \in \mathbf{Z}$: discrete–"time" index)

$$s[k] = \lambda_k = H(\Delta f \cdot k), \qquad k = 0,1,\ldots,D-1 \tag{9}$$

Let $x[k]$ and $y[k]$ denote the fading channel input and output signal, respectively, the input–output–relation reads

$$y[k] = s[k] \cdot e^{j\varphi_c} \cdot x[k] + n[k] \tag{10}$$

where φ_c is the carrier phase offset between transmitter and receiver, which can be assumed to be constant over at least one OFDM–symbol, and $n[k]$ represents the AWGN with variance $\sigma_n^2 = N_0 \cdot D \cdot \Delta f$ where N_0 is a one sided noise power spectral density. Applying the stochastic power line channel model discussed in the previous chapter, the fading gain $g[k] \cong |s[k]|$ has for a fixed "time" k, or equivalently for a fixed sub carrier number v, a Ricean distribution with the probability density function (pdf) ($I_0(\cdot)$ is the modified Bessel function of order zero)

$$p_G(g|v) = \frac{2g}{\sigma_v^2} \cdot \exp\left(-\left(\frac{g^2}{\sigma_v^2} + K_v\right)\right) I_0\left(2g\sqrt{\frac{K_v}{\sigma_v^2}}\right) \quad (11)$$

where

$$\sigma_v^2 = \frac{P(\Delta f \cdot v)}{K_v + 1} \quad (12)$$

and

$$K_v = \frac{m^2(\Delta f \cdot v)}{P(\Delta f \cdot v) - m^2(\Delta f \cdot v)} \quad (13)$$

are the usual parameters of a Ricean pdf. It is also interesting to consider the normalized channel state

$$\begin{aligned} \tilde{s}[k] &\cong \frac{s[k]}{\sqrt{P(\Delta f \cdot k)\sigma_k^2} \cdot e^{-j\varphi_0(\Delta f \cdot k)}} \\ &= \frac{s[k]}{\sqrt{(1+K_k)\sigma_k^2} \cdot e^{-j\varphi_0(\Delta f \cdot k)}} \end{aligned} \quad (14)$$

which corresponds to samples of the normalized transfer function from Equation (6). The normalized fading gain $\tilde{g}[k] \cong |\tilde{s}[k]|$ is Ricean distributed with parameters $\tilde{\sigma}^2$ and $\tilde{K}$ independent of the sub carrier number v thus, the power line fading channel model for OFDM transmission is here constructed by using the well–known Ricean flat fading channel model and multiplying each channel gain $\tilde{g}[k]$ with the corresponding amplitude term $\sqrt{P(\Delta f \cdot k)}$. Usually, adjacent OFDM-sub carriers are located within the coherence bandwidth B_c. Hence, the fading channel is slowly time–varying and the channel state can be expected to be constant over at least two consecutive symbols. For transmission over a series of OFDM–symbols, we define the discrete–"time" stochastic process

$s[\zeta,k], k \in \mathbf{Z}$, as stochastic model for the fading channel, where ζ denotes the atomic event of the corresponding random experiment. Each sample function $s[\zeta,k]$ corresponds to one exemplary power line channel. Now, the long term time variance of the power line channel has to be taken into consideration, too. As a proven model to describe this time variance has not been established yet, one reasonable choice is that one realization of $s[\zeta,k]$ contains random variables of one sample function $H(\eta,f)$ for fixed frequency values $f = \Delta f \cdot v$, $v = 0,1,2,\ldots,D-1$. However, since we are interested in results which are valid for an average of power line transmission scenarios, it is more convenient to identify a sample function of $s[\zeta,k]$ with a concatenation of many realizations of the discrete–frequency stochastic process $H(\eta,\Delta f \cdot v)$, $v = k \bmod D$. In this case, one fading channel realization represents an ensemble average over power line channel realizations.

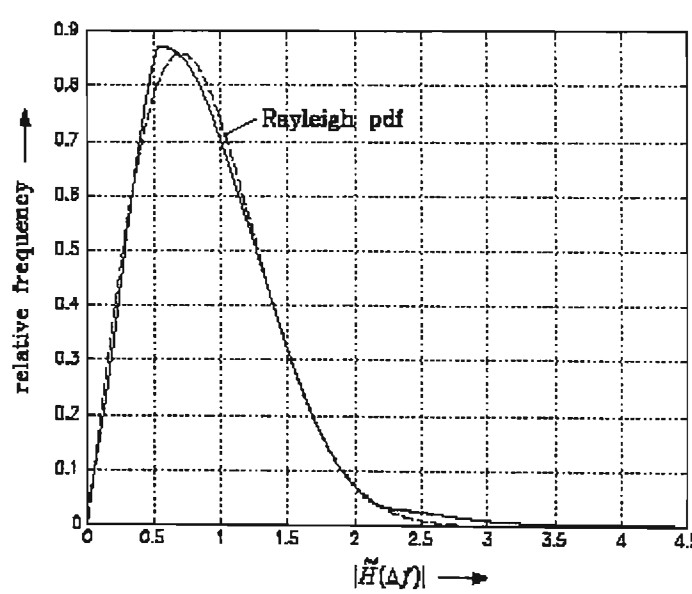

Figure 5.7: Histogram of the normalized channel transfer function $|\tilde{H}(\Delta f \cdot v)|$ for $1 < (\Delta f \cdot v)/MHz < 4$ (solid line) and Rayleigh pdf (dashed line)

Figure 5.7 shows the histogram of $|\tilde{H}(\Delta f \cdot v)|$ for $1 < (\Delta f \cdot v)/MHz < 4$ (solid line) assuming that the average power transfer function $P(f)$ is well approximated by equation

(4), where the attenuation parameter a is fitted to the sample transfer functions. The sub carrier spacing Δf is chosen appropriately small so that a sufficient number of samples of $\widetilde{H}(f)$ occur in the histogram. Clearly, the fluctuations of the curve are due to the relatively small available data base. For a comparison the Rayleigh pdf, which is the special case of the Ricean pdf with Ricean parameter K equal to zero, is plotted in Figure 5.7 (dashed line). As it can be seen, the pdf given by the stochastic model satisfactorily matches the histogram based on measurements.

5.4 CHANNEL CAPACITY

Having established a fading channel model for power line communications using OFDM, we are now in the position to calculate channel capacities as figure of merit to compare different transmission schemes. It should be noted that the capacities are expressed as ensemble averages. Thus, the capacities represent averages of achievable rates over an ensemble of power line channel realizations and they are not the achievable rates for all special channel realizations. Subsequently, we will distinguish the cases where information on the channel state and the carrier phase are and are not available at the receiver.

5.4.1 Coherent Transmission

The fading channel model introduced earlier in this chapter is applied and channel state information (CSI) is supposed to be available at the receiver side, i.e., the channel gain and phase are known. In this case, at least from the information theoretical point of view, the dependency between consecutive channel states, i.e., the channel memory is of no importance. But usually, in order to make standard coding techniques applicable, interleaving at the transmitter and deinterleaving at the receiver are performed leading to virtually memoryless channel between x and y. As full CSI is also passed through the deinterleaver, capacity is not affected by such an interleaving technique, of course. The corresponding system model for coherent transmission is sketched in Figure 5.8.

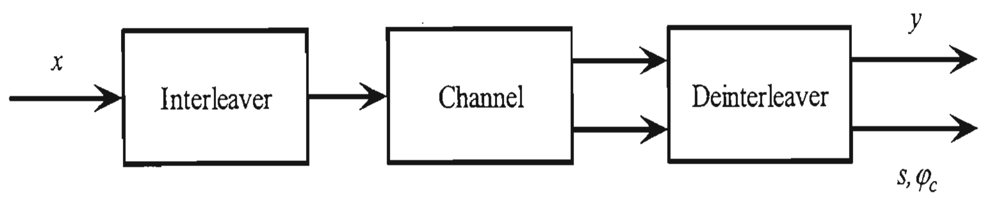

Figure 5.8: System model for coherent transmission (Source: Cogency [9,22])

The channel is described by the conditioned pdf $p_Y(y|x,s,\varphi_c)$. Since coherent reception is assumed and since the noise is rotationally invariant, the phase of $s[k]\cdot e^{j\varphi_c}$ is irrelevant and it is sufficient to consider $p_Y(y|x,g)$. Clearly, $p_Y(y|x,g)$ is the well–known two–dimensional Gaussian pdf with mean $g[k]\cdot x[k]$ [18]. The calculation of the channel capacity requires the optimization of all free parameters. As we are interested in the limits for given PSK and QAM signal constellations with uniformly, independently, and identically distributed signal points, i.e., constellation and a–priori probabilities are regarded as part of the channel, no optimization on these parameters has to be performed. For coherent reception and perfect channel state information, the capacity C_{CSI}, measured in bit per symbol, equals the average mutual information [35].

$$C_{CSI} = \varepsilon_{Y,X,G}\left\{\frac{p_Y(y|x,g)}{p_Y(y|g)}\right\} \tag{15}$$

where $p_Y(y|g)$ is the average pdf of the channel output given the channel state. For averaging over the channel state the pdf

$$p_G(g) = \frac{1}{D}\sum_{v=0}^{D-1} p_G(g|v) \tag{16}$$

with $p_G(g|v)$ from (11) is used.

5.4.2 Noncoherent Transmission

In many communications scenarios reliable estimation of the channel state and carrier phase is not practicable. For such applications the use of differential encoding at the transmitter and noncoherent reception at the receiver are convenient. Figure 5.9 shows the system model for noncoherent transmission. By differential encoding the information is conveyed in the transitions of the channel input symbols x. The current transmitted symbol $x[k]$ is determined by an interleaved version of the data carrying (differential) symbol $a[k]$ and the previous transmitted symbol $x[k-1]$.

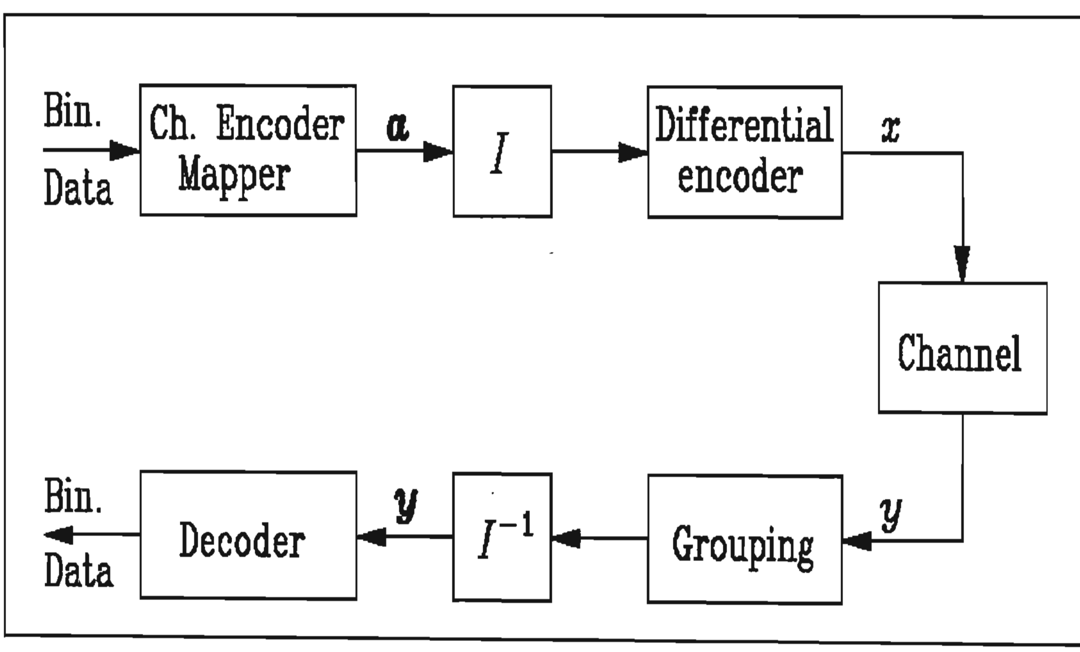

Figure 5.9: System model for noncoherent transmission (Source: Cogency [9,22])

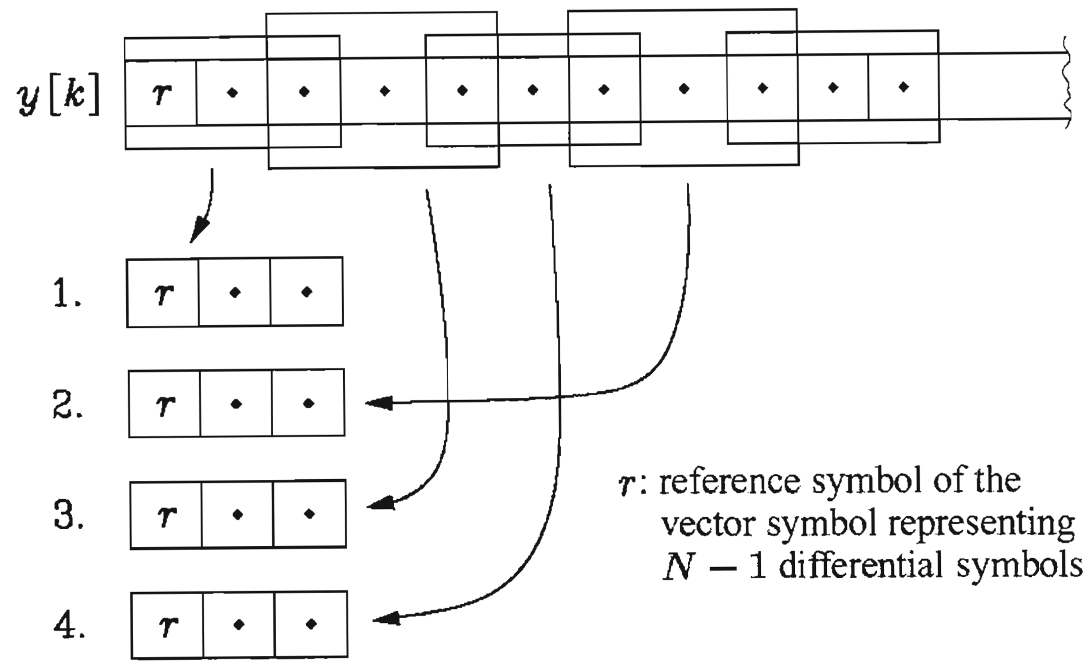

Figure 5.10: Grouping of the received sequence $y[k]$ into overlapping vectors y of length $N = 3$ and deinterleaving (Source: Cogency [9,22])

For high bandwidth efficiency this differential encoding is performed in both phase and amplitude, which is known as differential amplitude and phase shift keying (DAPSK). Suitable signal constellations are $\alpha\,\mathrm{A}\beta\,\mathrm{PSK}$ for the symbols x, which consist of $M = \alpha \cdot \beta$ points arranged in α distinct concentric rings with different radii ρ_i, $i = 0,1,2,...,\alpha - 1$, and β uniformly spaced phases φ_m, $m = 0,1,2,...,\beta - 1$, so–called "star– constellations" [37]. As usual, the differential symbols α are taken from the same signal set as the transmitted signal. Let $i[k]$ and $m[k]$, $k \in \mathbf{Z}$, denote the sequences of radius and phase indices of the corresponding sequence $x[k]$ of channel symbols, i.e., $x[k] = \rho_{i[k]} e^{j\varphi_{m[k]}}$. Additionally, the radius and phase indices of the differential symbols $a[k]$ are written by $j[k]$ and $n[k]$, i.e., $a[k] = \rho_{j[k]} e^{j\varphi_{n[k]}}$. Then, differential encoding is performed by

$$x[k] = \rho_{(i[k-1]+j[k]) \bmod \alpha} e^{j\varphi_{(m[k-1]+n[k]) \bmod \beta}} \tag{17}$$

In conventional differential detection the discrete channel output sequence $y[k]$ is partitioned into overlapping vectors $\boldsymbol{y}$ of two consecutive symbols at the receiver. If the coherence bandwidth of the channel is at least N>2 symbols the receiver favourably operates on blocks $\boldsymbol{y}$ of N>2 consecutive symbols, overlapping each other by one symbol, see Figure 5.10 (where N=3). This multiple symbol differential detection provides further gains [38, 39]. From the observation of one received vector $\boldsymbol{y}$, decision variables on the differential vector $\boldsymbol{a}$ of N-1 data symbols a are obtained. Thereby, $\boldsymbol{y}$ corresponds to the vector $\boldsymbol{x}$ containing N transmitted symbols x, where the first entry acts as reference symbol r of the differential encoder. In order to apply standard coding techniques for memoryless channels, it is convenient to ignore the statistical dependencies between the blocks $\boldsymbol{y}$. This is generated by applying (asymptotically ideal) interleaving based on vector symbols $\boldsymbol{a}$ and $\boldsymbol{y}$, respectively, which generates a virtually memoryless channel between $\boldsymbol{a}$ and $\boldsymbol{y}$. Figure 5.10 illustrates overlapping, grouping, and deinterleaving for N=3.

Although the current channel gains $g[k]$ are assumed to be unknown to the receiver, it is reasonable to exploit the well–known average channel parameters σ_v^2 and K_v introduced in (12) and (13), respectively, for each OFDM–sub carrier $v = 0,1,2,\ldots,D-1$. Here, each vector symbol $\boldsymbol{a}$ and $\boldsymbol{y}$, respectively, corresponds to N sub carriers. Since a verified model of the acf of the channel gain has not been found yet, we employ the usual assumption that the channel gain is almost constant over at least N sub carriers. Thus, the memoryless channel is represented by the pdf $p_Y(y|a,v)$, where the dependency on σ_v^2 and K_v is expressed by conditioning on one sub carrier number v of the N consecutive sub carriers. In order to determine $p_Y(y|a,v)$ the fading channel input–output–relation (10) is extended to vector symbols

$$y[l] = s[l] \cdot e^{j\varphi_c} \cdot x[l] + n[l] \tag{18}$$

where $\boldsymbol{s}[l]$ is nearly equal for all components of $\boldsymbol{x}[l]$, $\boldsymbol{n}[l]$ denotes independent AWGN with variance $\sigma_n^2 = N_0 \Delta f D$ per complex component, and $l=[k(N\text{-}1)] \in \mathbf{Z}$ denotes the discrete–"time" index corresponding to vector symbols. Replacing $\boldsymbol{a}$ by $\boldsymbol{x}$ and one reference symbol r according to (17), $p_Y(y|x,v)$ can be expressed by $p_Y(y|a,r,v)$. This pdf includes inversion of the differential encoding. Averaging this pdf over all possible reference symbols r finally yields the desired pdf $p_Y(y|a,v)$. Now, the capacity of the memoryless vector channel, normalized to bit per scalar symbol, is calculated by

$$C(N) = \frac{1}{N-1} \cdot \frac{1}{D} \sum_{v=0}^{D-1} \varepsilon_{Y,A} \left\{ \log_2 \frac{p_Y(y|a,v)}{p_Y(y|v)} \right\} \qquad (19)$$

It should be noted that no optimization of the distribution of $\boldsymbol{a}$ can be performed. Regardless the distribution of $\boldsymbol{a}$ the differentially encoded symbols x will be uniformly distributed. Therefore, we had already restricted the differential symbols $\boldsymbol{a}$ to be uniform, independently, and identically distributed, which maximizes the throughput of the channel.

CHAPTER SIX

PERFORMANCE EVALUATION OF POWER LINE COMMUNICATION SYSTEM

6.1 NUMERICAL RESULTS

In this chapter, capacities over the average signal–to–noise ratio $\overline{E}_s/N_o$ ($\overline{E}_s$: average receive energy per symbol) are evaluated by numerical integration. The results are independent of the number D of OFDM–sub carriers and the sub carrier spacing Δf as long as $N \cdot \Delta f << B_c$ holds. For the following numerical results we suppose the channel gains $g[k]$ corresponding to sub carriers $v=k \bmod D$ to be Rayleigh distributed, which is the most important special case of the Ricean fading model. The average power transfer function $P(f)$ with exponential decay in f, i.e.,

$$\sigma_v^2 = P(\Delta f \cdot v) \propto \exp(-a \cdot \Delta f \cdot v) \tag{20}$$

The attenuation parameter a is set to 10^{-7} 1/Hz and 10^{-6} 1/Hz, respectively, typical for some classes of power line channels. Furthermore, the transmission bandwidth B_T assumed to be limited to 2 MHz and 3 MHz, respectively, which are reasonable values regarding restrictions imposed on power line communications by regulator authorities [40]. It should be noted that the capacity in bit per channel versus $\overline{E}_s/N_o$ depends on the transmission bandwidth because, via the average power transfer function $P(f)$, the channel fading properties depend on B_T. Although the channel parameters are only exemplary chosen, the subsequently drawn consequences apply in general.

6.1.1 Coherent Transmission

Coherent transmission with perfect channel state information and usual 4PSK, 8PSK, 16QAM, 32QAM, and 64QAM providing spectral efficiencies up to 6 bit/s/Hz is considered.

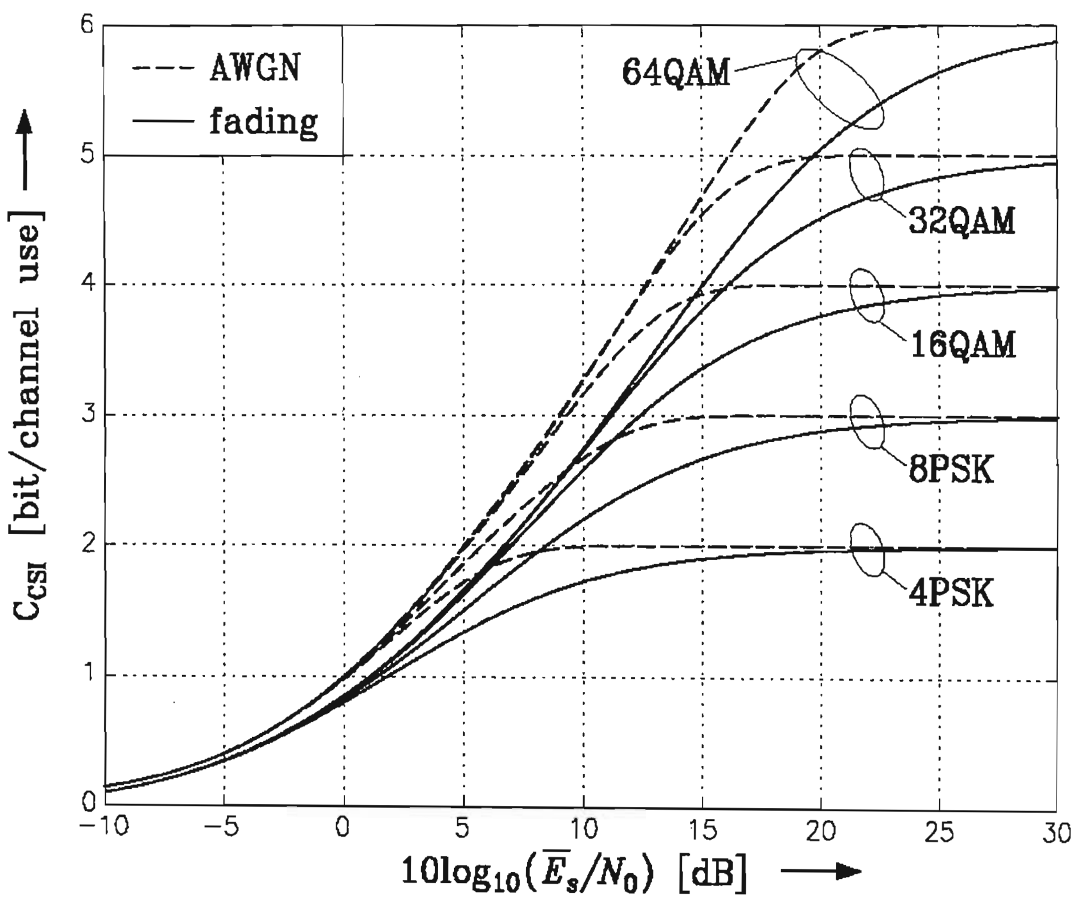

Figure 6.1: Capacities C_{CSI} (coherent reception) for 4PSK, 8PSK, 16QAM, 32QAM, 64QAM. Solid lines: Fading channel of OFDM over power lines with parameters $a = 10^{-7}$ 1/Hz and $B_T = 3$ MHz. Dashed lines: AWGN channel.

Figure 6.1 presents the capacity curves for 10^{-7} 1/Hz and B_T =3 MHz. As reference, the respective capacities of the AWGN channel are shown. As expected, for a fixed information rate, the fading channel of OFDM transmission over power lines requires a considerably higher SNR than the AWGN channel. Furthermore, it is interesting to recognize that for the AWGN channel the curves of different signal constellations converge much faster towards lower capacity values than for the fading channel. Hence, in terms of capacity it is advantageous to spend more than one bit of redundancy per complex symbol [41], i.e., larger signal constellations in combination with low rate codes is favourably used. The same observation based on bit error rates has also been reported in many texts, where this strategy is called channel symbol expansion diversity (CSED).

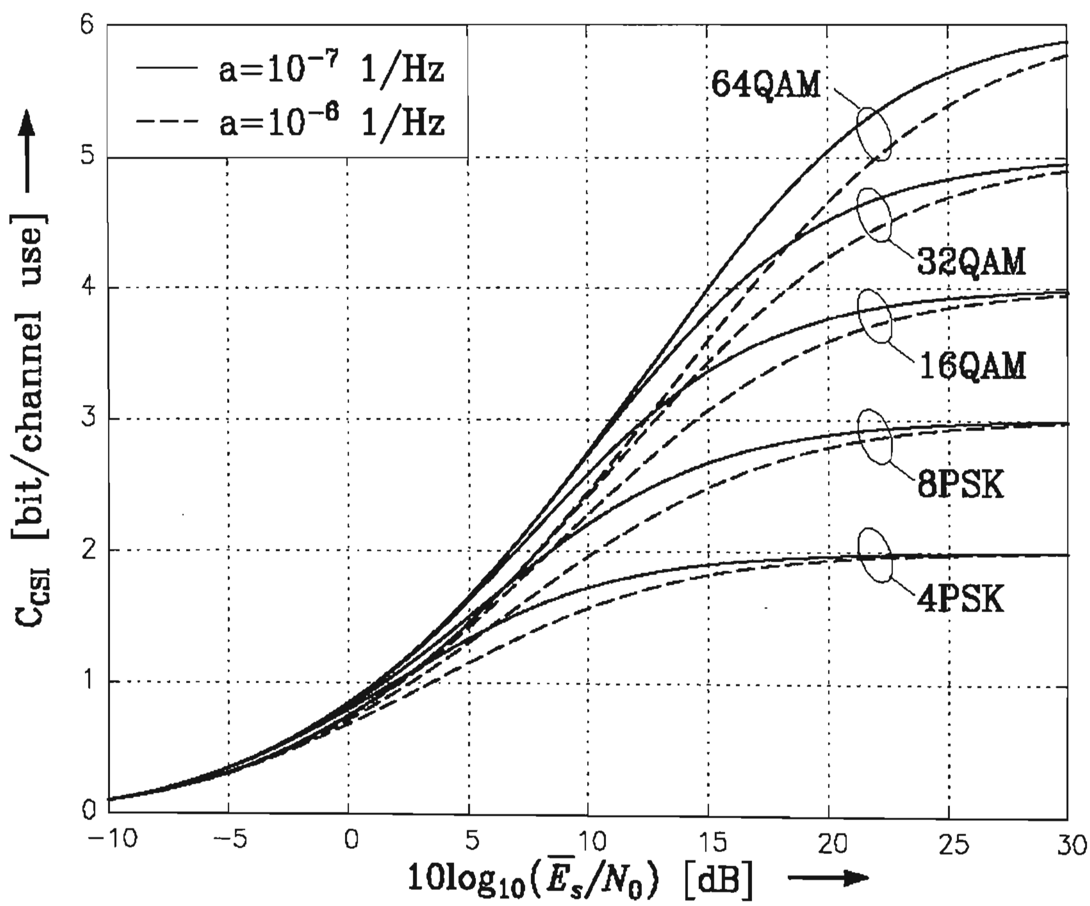

Figure 6.2: Capacities C_{CSI} (coherent reception) for 4PSK, 8PSK, 16QAM, 32QAM, 64QAM. Fading channel of OFDM over power lines with B_T =3 MHz. Solid lines $a = 10^{-7}$ 1/Hz. Dashed lines: $a = 10^{-6}$ 1/Hz.

In Figure 6.2 the influence of the parameter a on the capacity is illustrated. As can be seen, the capacity at a certain SNR decreases for the larger value of a. In the case of $a = 10^{-7}$ 1/Hz the fading variances σ_v^2 are almost identical for all v, and hence, the channel is essentially Rayleigh fading ($p_G(g)$ in (17) is the Rayleigh pdf), whereas for $a = 10^{-6}$ 1/Hz the variances vary strongly over the sub channel number, and thus, the channel gain fluctuates more heavily. Regarding the capacity curves of different constellations the concept of CSED is expected to provide higher gains for increasing a. Concerning the capacity over the average SNR, using a larger transmission bandwidth is equivalent to increasing the value of a. Figure 6.3 shows the capacity curves for B_T = 2 MHz and B_T = 3 MHz.

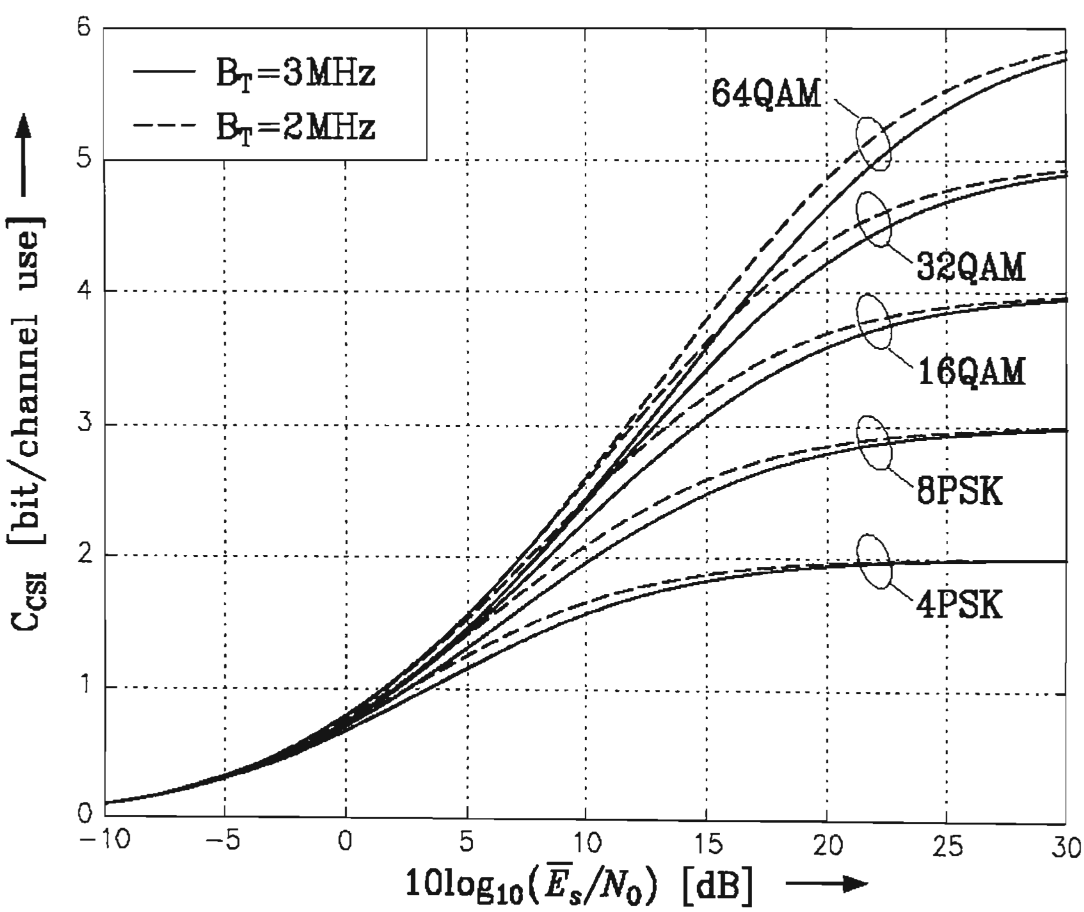

Figure 6.3: Capacities C_{CSI} (coherent reception) for 4PSK, 8PSK, 16QAM, 32QAM, 64QAM. Fading channel of OFDM over power lines with $a = 10^{-6}$1/Hz. Solid lines: $B_T = 3$ MHz. Dashed lines: $B_T = 2$ MHz.

For a bandwidth of 3 MHz the channel gain experiences a stronger fading which leads to a performance loss compared to the case of B_T = 2 MHz. Therefore, as long as $\exp(-a \cdot f)$ does not deviate negligibly from one, relatively large signal constellations should be applied for power line transmission over a wide spectral range. Although the capacity in bit per channel decreases for increasing transmission bandwidth B_T due to more severe fading, transmission capacity measured in bit per second increases with increasing B_T because of a higher possible number of channel uses per second.

6.1.2 Noncoherent Transmission

Differentially encoded transmission and differential detection is regarded without channel state information. The rings of the Dα Aβ PSK constellations are geometrically spaced with the ratios $\rho_1/\rho_0 = 2$ for α = 2 and $\rho_{i+1}/\rho_i = 1.4$ for i = 0,1,2 for α = 4, which were found to be advantageous for fading channels [42, 43]. Note, optimally the ring ratios have to be optimized for each SNR.

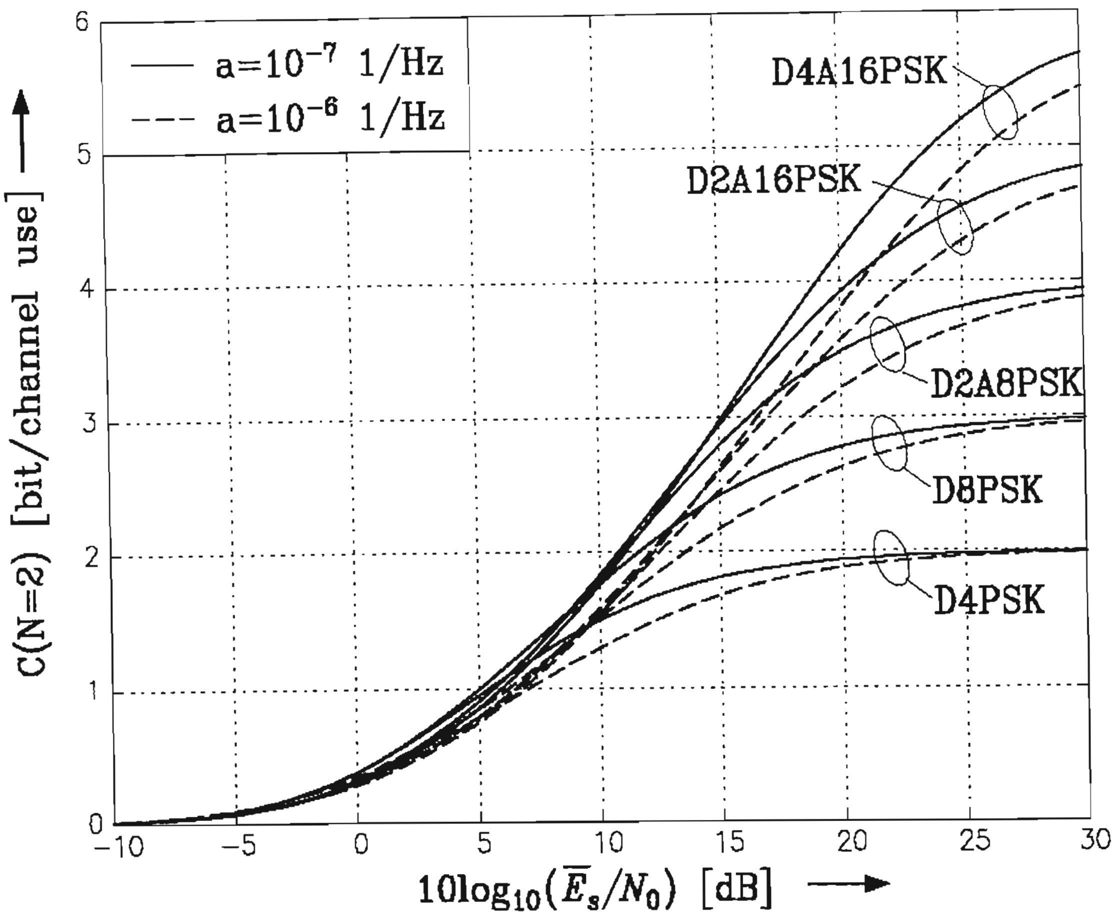

Figure 6.4: Capacities C_{CSI} (conventional differential reception) for D4PSK, D8PSK, D2A8PSK, D2A16PSK, D4A16PSK. Solid lines: Fading channel of OFDM over power lines with parameters $a = 10^{-7}$ 1/Hz and $B_T = 3$ MHz. Dashed lines: $a = 10^{-6}$ 1/Hz

Figure 6.4 comprises the capacity curves of various Dα Aβ PSK constellations, which offer spectral efficiencies up to 6 bit/s/Hz, and noncoherent detection with $N = 2$. The parameters of the power line channel are $a = 10^{-7}$ 1/Hz and $a = 10^{-6}$ 1/Hz, respectively, and $B_T = 3$ MHz. Since the ring ratios are fixed, the capacity curves for DAPSK and DPSK intersect. Consequently, CSED is not expected to provide gains for relatively low target rates, e.g., 2 bit/channel use for $a = 10^{-7}$ 1/Hz. However, if high spectral efficiencies are desired, gains can be achieved by spending more than one bit of redundancy per symbol. Moreover, for increasing a the positive effect of CSED intensifies. Similar to the case of coherent transmission, the capacity loss due to fading strongly depends on the parameter a (For clarity, the respective capacity curves of the AWGN channel are omitted in Figure 6.4.).

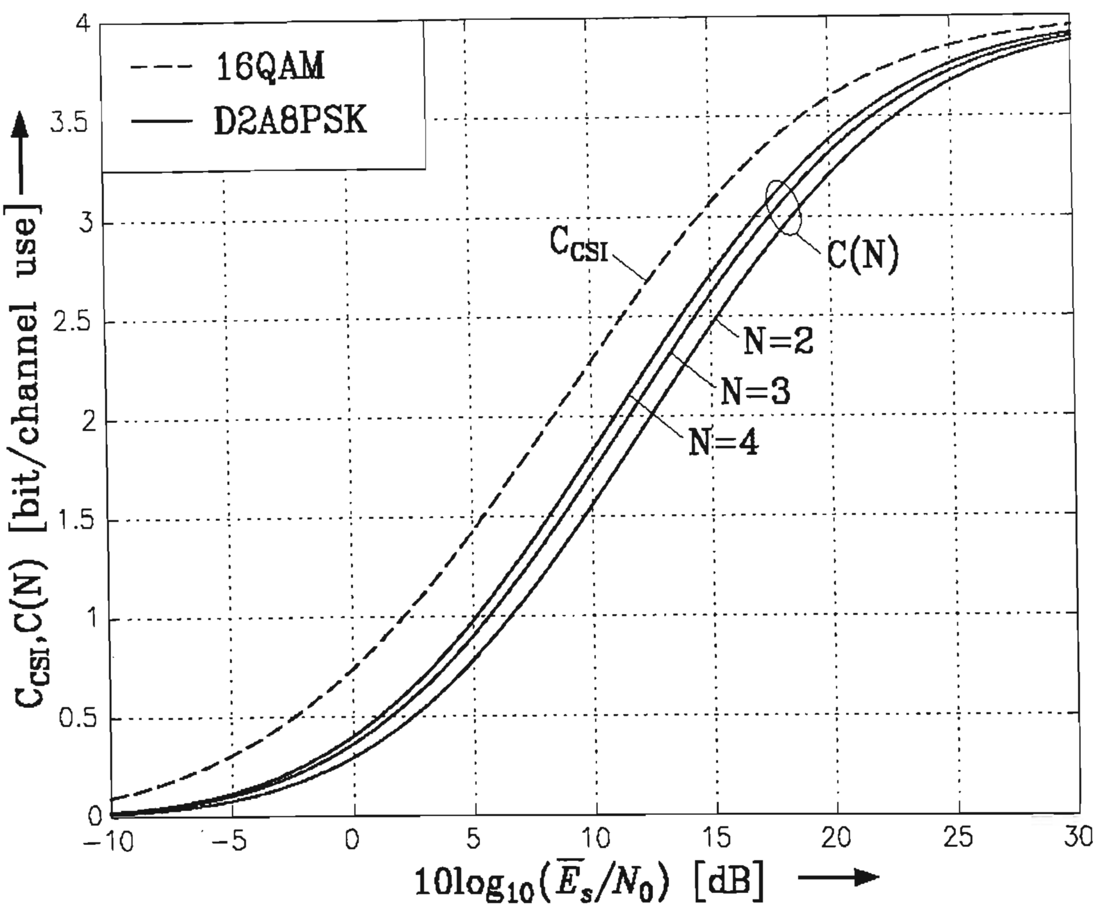

Figure 6.5: Capacities C_{CSI} and $C(N)$ for 16QAM and D2A8PSK, respectively. Fading channel of OFDM over power lines with $a = 10^{-7}$ 1/Hz and $B_T = 2$ MHz. Solid lines: $C(N = 2,3,4)$ (from right to left). Dashed lines: C_{CSI}.

In order to assess the performance loss because of differential detection, Figure 6.5 displays the capacities for coherent and noncoherent transmission with 16QAM and D2A8PSK, respectively. In the case of conventional differential detection, i.e., $N = 2$, a loss of 3 to 5 dB of signal–to–noise ratio for differentially encoded transmission compared to coherent transmission is recognizable. By applying multiple symbol differential detection this gap can be compensated in part as shown in Figure 6.5 for $N = 3,4$. If N approaches infinity the normalized capacity $C(N)$ converges to C_{CSI}, [44].

6.2. SIMULATION RESULTS

In order to further assess the capabilities of power line communications, different transmission scenarios have been simulated. In particular, 8PSK and 16QAM transmission with coherent reception and perfect channel state information at the receiver and 8PSK differentially encoded transmission (D8PSK) with (conventional) differential detection for $N = 2$ over the power line fading channel are considered. Again, the Rayleigh fading model for the sub channel transfer factors with variances according to equation (20) is used. The attenuation parameters are chosen $a = 10^{-6}$ 1/Hz and $a = 10^{-7}$ 1/Hz, respectively, and transmission bandwidth is $B_T = 3$ MHz.

As this is a coded modulation scheme we apply bit–interleaved coded modulation (BICM) [45, 46] in combination with Gray labelling of the signal points. BICM is a suboptimum but simple scheme applying only one binary code. For several applications it has been shown [46] that based on Gray labelling BICM suffers only a marginal capacity loss compared to optimum coded modulation via multilevel coding (MLC) with multistage decoding (MSD) [48]. Parallel concatenated convolutional codes (Turbo codes) [52] perform close to the capacity limit and are thus used as codes. We employ Turbo codes with 16 state constituent codes and random interleavers. Rate is adjusted by symmetric puncturing of parity symbols [49]. In the decoding 6 iterations are executed.

The code lengths are chosen in that way that the code symbols of one code word are mapped to 1000 channel symbols. As the use of $D \geq 1000$ sub carriers is practical regarding the bandwidth of 3 MHz, coding can be done separately for each OFDM–symbol. If bit-interleaving is also restricted to one OFDM–symbol, the transmission delay is limited to 1000 channel symbols. However, in order to obtain results that are not affected by the special choice of the autocorrelation function $\phi_{\tilde{H}\tilde{H}}(f)$ for which a proved model does not exist, ideal symbol interleaving is simulated by generating the sub channel transfer factors λ_v, $v = 0,1,2,\ldots,D\text{-}1$, independently of each other. If the coherence bandwidth of the power line channel is negligible compared to the interleaving depth, this model is appropriate. In all simulations, the bit–interleavers are randomly generated in order to provide results independent of a particular chosen interleaver.

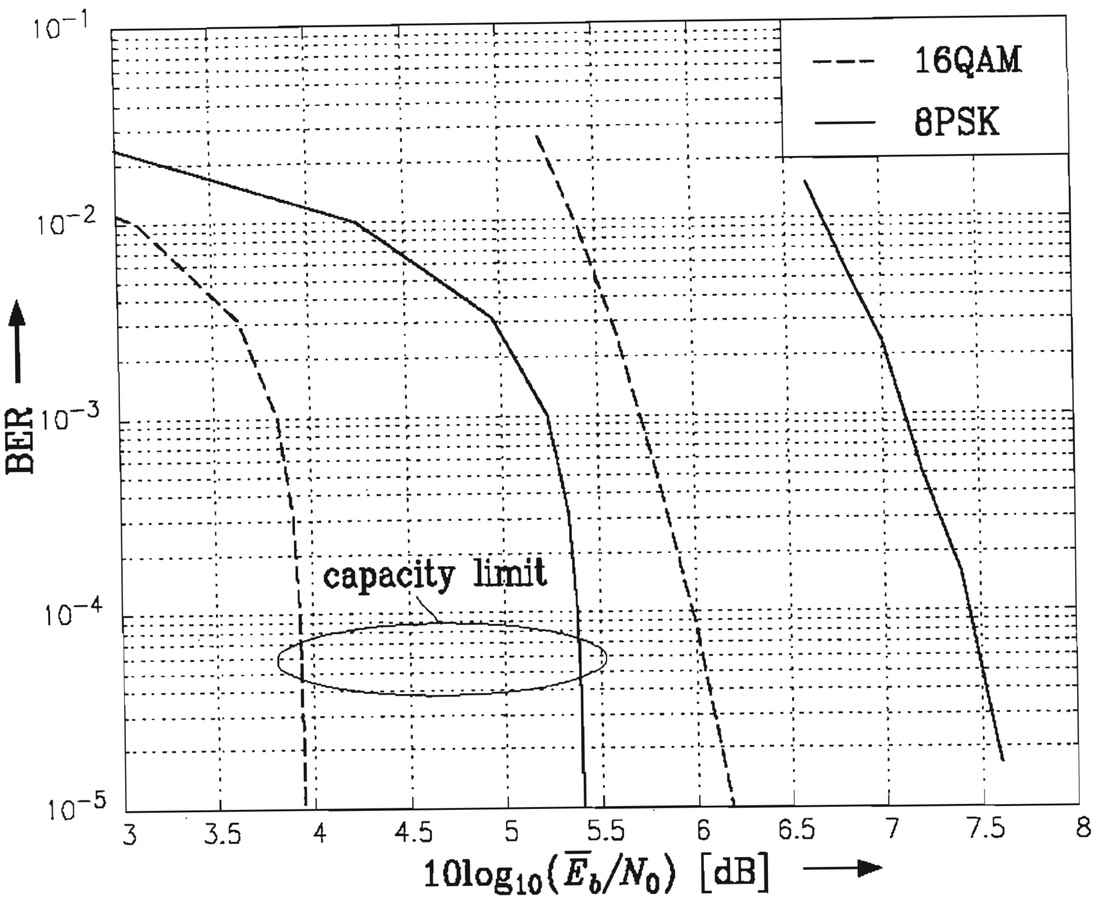

Figure 6.6: BER as a function of E_b/N_o for coherent transmission with 8PSK (solid lines) and 16QAM (dashed lines) and rate 2.0 bit/symbol. Fading channel of OFDM over power lines with $a = 10^{-7}$ 1/Hz and B_T = 3 MHz. Channel coding over one OFDM–symbol. BICM with ideal interleaving. Left hand side: respective rate–distortion capacity limits.

In Figure 6.6 the bit error rates (BER) of coherent transmission using 16QAM and 8PSK for a target rate equal to 2.0 bit/symbol are compared. The lengths of the binary codes are 4000 for 16QAM and 3000 for 8PSK, respectively, i.e., 1000 OFDM–sub carriers are active. Ideal interleaving is applied as indicated above. As reference, the capacity limits taking the finite error rate into account ("rate–distortion capacities") are shown [50]. As can be seen, 16QAM clearly outperforms 8PSK. This is due to the higher constellation expansion diversity when 16QAM with code rate 1/2 is applied to achieve the desired target rate of 2.0 bit/symbol. The gap of about 1.5 dB between the curves simulated for 8PSK and 16QAM matches the result predicted by the capacity analysis, which is illustrated by the rate–distortion capacities. For BER's around 10^{-4} the gap between the required signal–to–noise ratios and the capacity limits is about 2 dB.

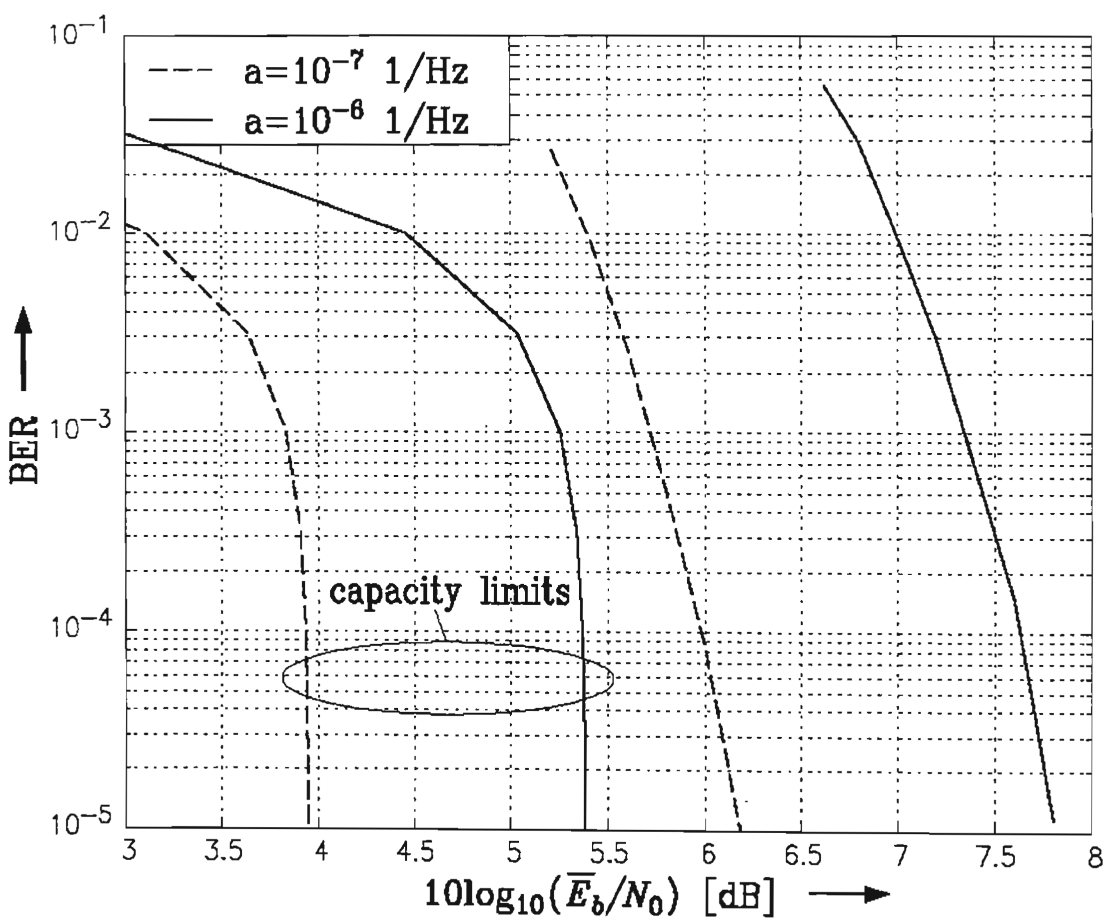

Figure 6.7: BER as a function of E_b/N_o for coherent transmission with 16QAM and rate 2.0 bit/symbol. Fading channel of OFDM over power lines with B_T = 3 MHz and $a = 10^{-6}$ 1/Hz (solid lines) and $a = 10^{-7}$ 1/Hz (dashed lines), respectively. Channel coding over one OFDM–symbol. BICM with ideal interleaving. Left hand side: respective rate–distortion capacity limits.

Coherent transmission with 16QAM over power line channels with different attenuation parameters a is regarded in Figure 6.7. Clearly, the stronger fading due to a larger value of a leads to a performance loss. In particular, the power efficiency decreases by about

1.7 dB when a increases from 10^{-7} 1/Hz to 10^{-6} 1/Hz. Again, the simulation results are in great accordance with the rate–distortion capacities. As mentioned in Chapter 5, the channel memory does not play any role for the capacity of the coherent transmission scheme. But if the channel coherence bandwidth is relatively large and interleaving is done within one OFDM–symbol, a decoding error is caused with high probability when deep fades occur, which leads to an increased average error rate. In order to study these effects in more detail, we use a simple model for the normalized stationary Gaussian process $\widetilde{H}(\eta, f)$, i.e., a Gaussian acf

$$\phi_{\widetilde{H}\widetilde{H}}(f) = \exp(-\pi(f/B_c)^2) \tag{21}$$

The simulation results for different values of the coherence bandwidth B_c are depicted in Figure 6.8 (a = 10^{-7} 1/Hz, B_T = 3 MHz). Again, randomly generated bit–interleavers are applied. The curves show that the channel memory cannot completely be eliminated by the bit-interleaving within one OFDM–symbol, i.e., for a larger B_c the bit error rate deteriorates. For the coherence bandwidths comprising 5 and 11 OFDM–sub channels, respectively, the losses in power efficiency are about 0.2 dB and 0.6 dB, respectively, for BER $\approx 10^{-4}$. Although the interleaving depth of 1000 channel symbols is still relatively large when compared to the coherence bandwidth of e.g. 11 channel symbols, this effect occurs because of the high sensitivity of the Turbo code to statistical dependencies within the received symbol sequence.

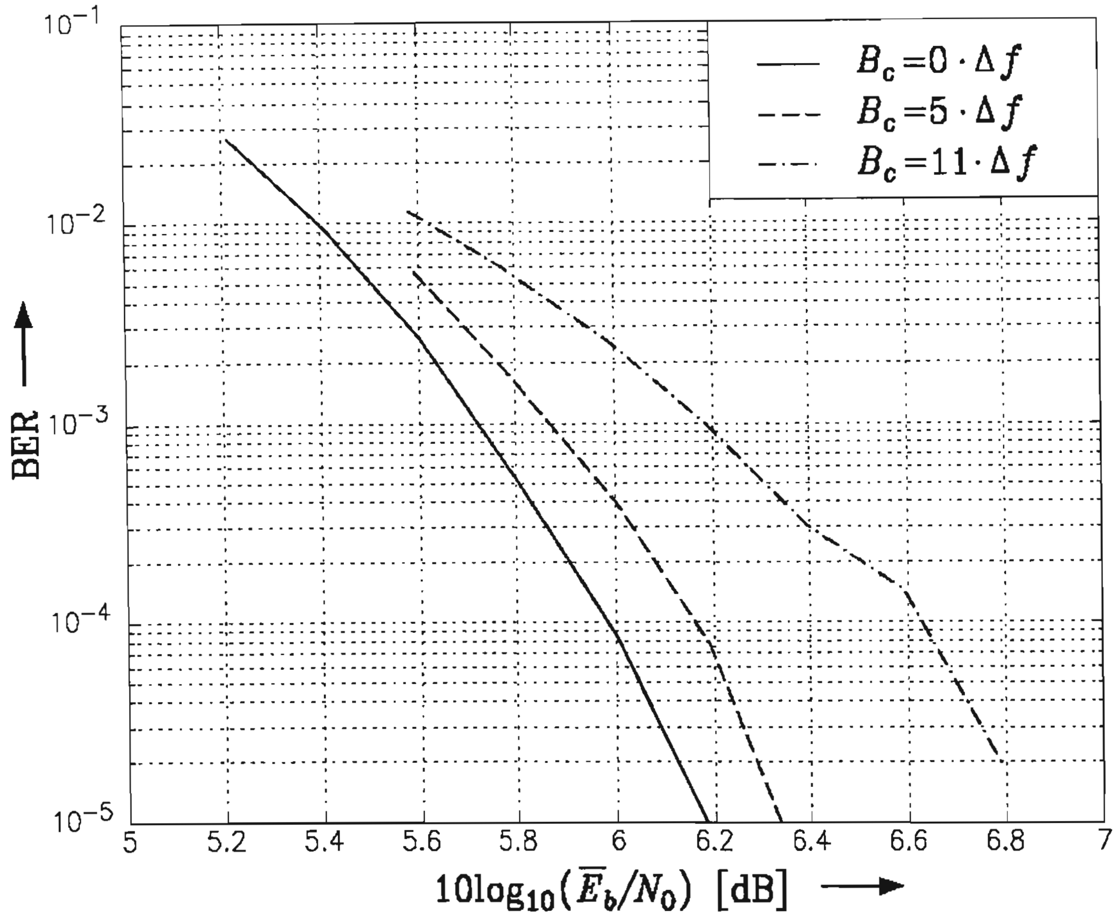

Figure 6.8: BER as a function of E_b/N_o for coherent transmission with 16QAM and rate 2.0 bit/symbol. Fading channel of OFDM over power lines with $a = 10^{-7}$ 1/Hz and $B_T = 3$ MHz. Autocorrelation function $\phi_{\tilde{H}\tilde{H}}(f)$ according to (21). Coherence bandwidth: $B_c = 0$ Hz (solid line), $B_c = 5 \cdot \Delta f$ (dashed line), $B_c = 11 \cdot \Delta f$ (dash–dotted line). BICM (channel coding and random interleaving) over one OFDM– symbol.

Finally, coherent transmission with channel state information and differentially encoded transmission without channel state information using the 8PSK signal constellation are compared. Here, ideal interleaving is simulated, and for D8PSK the channel is assumed to be constant over two consecutive symbols. The target rate of 1.5 bit/symbol is chosen. In Figure 6.9 the simulation results are plotted.

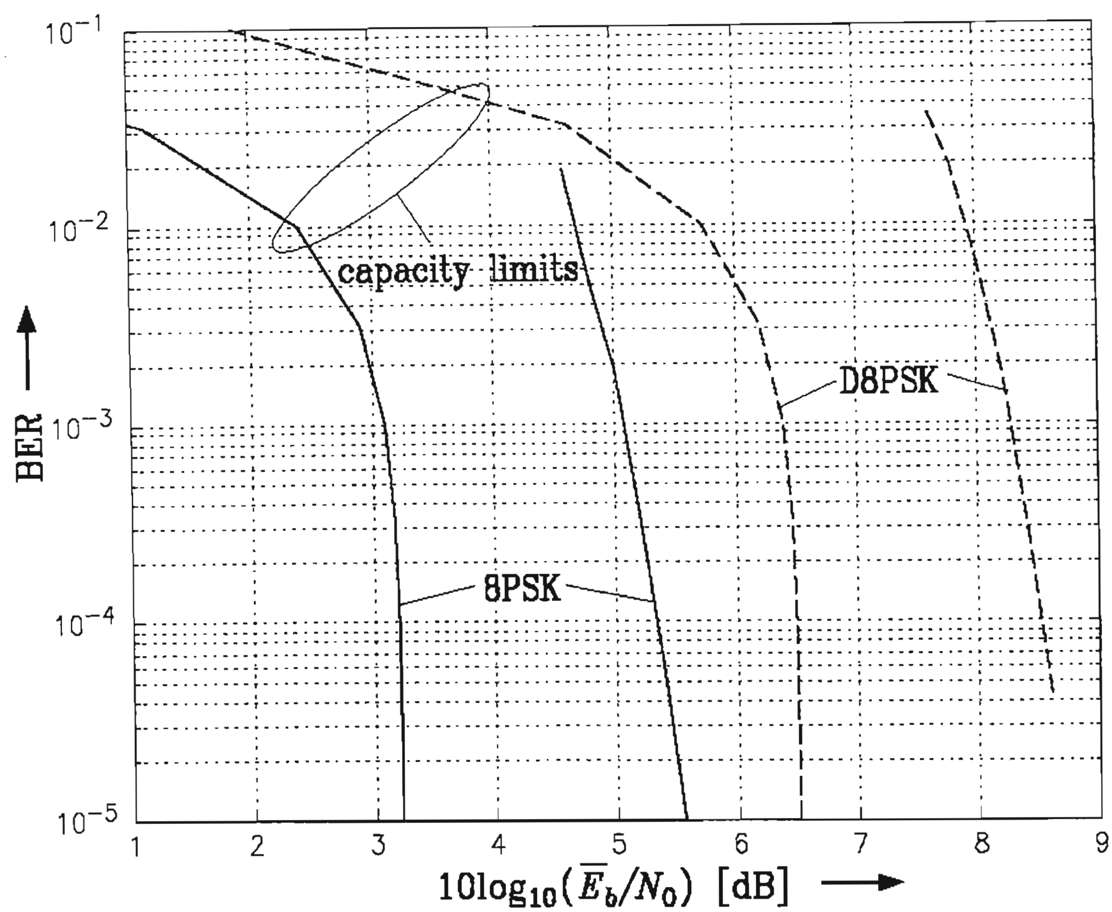

Figure 6.9: BER as a function of E_b/N_o for 8PSK (solid lines) and D8PSK transmission and differential detection with $N = 2$ (dashed lines) and rate 1.5 bit/symbol. Fading channel of OFDM over power lines with $a = 10^{-7}$ 1/Hz and $B_T = 3$ MHz. Channel coding over one OFDM– symbol. Ideal interleaving. Left hand side: respective rate–distortion capacity limits.

As predicted by the theoretical considerations, a difference in the power efficiencies of about 3 to 3.5 dB between coherent and noncoherent transmission can be observed. An increase of the observation interval with $N > 2$ is expected to reduce the gap. But it should be noted that for $N > 2$, BICM is not the appropriate scheme [51]. High performance PLC can now be considered a mature technology, based on the well-known improved OFDM engines.

6.3 POWER LINE TECHNOLOGY PRACTICAL EQUIPMENTS

6.3.1 Introduction

Since PLT has not been extensively deployed in South Africa, and owing to the fact that there are in place few experimental site for PLT, we had to settle for the use of the equipment at the University of Fort Hare Centre of Excellence (CoE) provided by Ascom. Ascom is an international provider of services for telecommunication systems, integrated voice and data communications, wireless and corded security solutions and networked revenue collection systems. As a strong supporter and pioneer of PLT, Ascom has continuously and systematically developed this technology for the broadband access as well as for the in-house distribution of data.

The University of Fort Hare is located about 120 km from Port Elizabeth in a place which is a bit more of a village than urban poor. There are no busy main roads and there are overhead high tension lines running near by the university. The observed experiments were carried out in the Department of Computer Science, which houses the CoE. The software provided enabled the user to determine or measure the throughput variation using different adapters provided by Ascom (i.e. the 1.5 Mbps and the 4.5 Mbps Ascom adapters). The A typical SNR measured by Ascom using their adapters is shown in Figure 6.10.

In the experimental set up, it is possible to measure the throughputs between clients and also between client and server. The file size transferred in intervals of 500 milliseconds for 50 seconds and the file transfer rate are then measured. The ASCOM adapters used carriers of 19.8, 22.8 and 25.2 MHz with data rates of up to 4.5 Mbps. A bandwidth of 2 MHz/carrier using GMSK (Gaussian Minimum Shift Keying) modulation with a delay of less than 25 milliseconds and a total power consumption of less than 10 W were the specifications for the adapters used.

The throughputs of the clients were observed on the server since the server was connected to the master unit. The coupling method that was used was the conductive type although inductive coupling was favoured. The reason for using the conductive coupling method was because at the time of measurements some of the inductive coupling components were not available (viz. the ferrite rings).

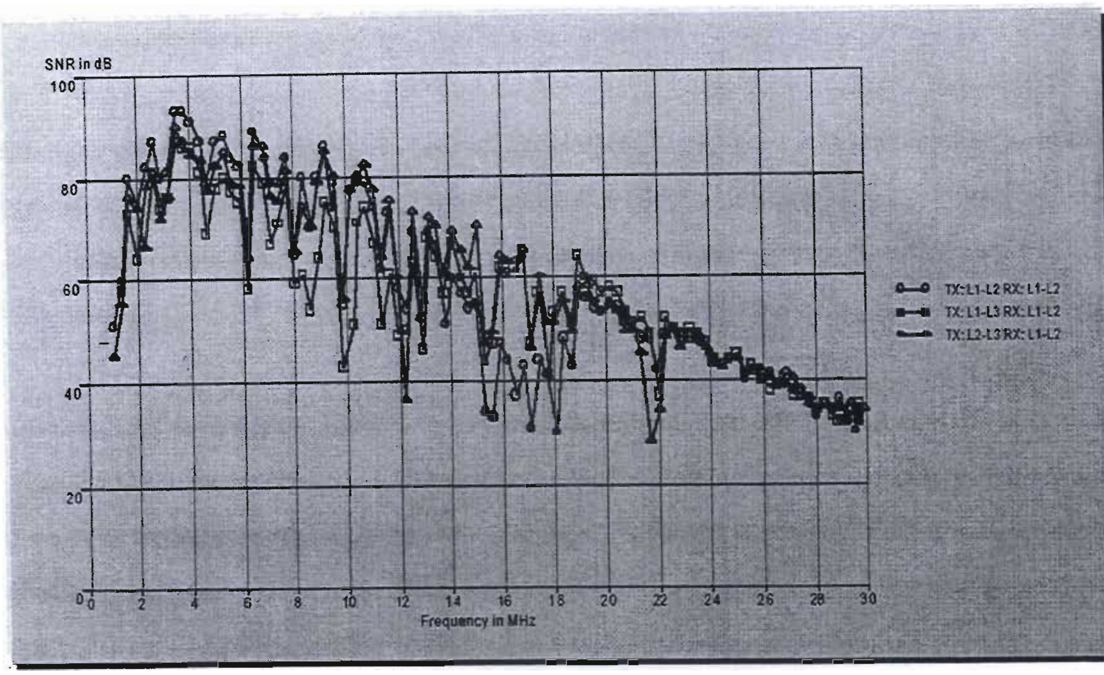

Figure 6.10: Typical signal–to–noise ratio (Source : Ascom [71])

6.3.2 Basic Coupling Methods And Components

The power line signal can be coupled to the power mains via conductive coupling, or inductive coupling [71]. The basic differences of the two injection methods are from a physical point of view, with the conductive coupling a voltage is applied between the two conductors that are used for the coupling. To achieve this, a galvanic connection is made to the power grid, while with the inductive coupling a current is injected into the two conductors. This is achieved through an inductive "transformer" coupling using ferrites. The most important aspects are:

Conductive injection: The conductive injection method is most effective when the mains impedance is high at the signal injection point. This is typically the case at simple house access points where a single power cable is entering and another single cable is leaving the connection point.

Inductive injection: The inductive injection method is most effective when the mains impedance is low at the signal injection point. This is typically the case when injecting into a bus system where several power cables are connected together. Connecting several power cables to a single point or bus effectively results in a parallel connection of the individual cable impedances. This results in a low impedance.

6.3.3 Conductive Coupling And Components

With the conductive coupling method (see Figure 6.11), the power line signal is injected into the power grid via the power cable of the unit or via signal coupling units [71].

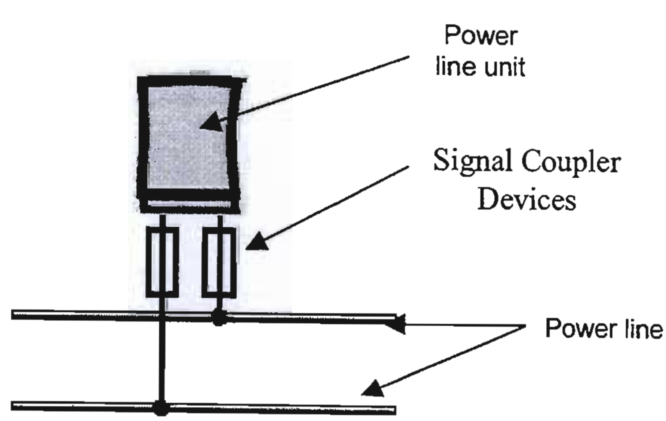

Figure 6.11: Conductive coupling of power line signal to power mains (Source: Ascom [71])

The conductive signal coupling is used:

- When the mains impedance is high (> 20 Ohms),

- when there is no need for the more efficient inductive coupling due to high signal levels,
- when there is no space for the inductive coupling elements.

The drawbacks of the conductive signal coupling are:

- High coupling loss at coupling points with low impedance (< 20 Ohm),
- normally the electricity must be switched off for the installation of the power line units.

The conductive signal coupling is the inherent method. Whenever a power line unit is connected to the power mains via the provided cable, the unit is coupled conductively. Bridging large distribution panels (with large signal losses) with conductive coupling is achieved with Signal Coupler Devices (SCD), and Signal Distribution Box (SDB).

The signal coupler device (or signal coupler for short) is used to make the galvanic connection to the power mains and to decouple the signal port from the dangerous mains voltage. It also includes the required over voltage protection elements. The signal coupler can be used to build a phase/phase or a phase/neutral injection. For each galvanic coupling point one signal coupler must be installed. The signal distribution box is a passive signal splitter. It has one input port and 6 or 11 output ports, depending on the model. The input port is connected to the power line unit. Using an Ethernet patch cable an output port is connected to a signal coupling unit. The 6- port signal distribution box results in a loss (as seen by a single injection point) of about 10 dB, the 11-port version of about 14 dB.

6.3.4 Inductive Coupling Method

The inductive coupling method is the preferred method for the power line infrastructure units [71].

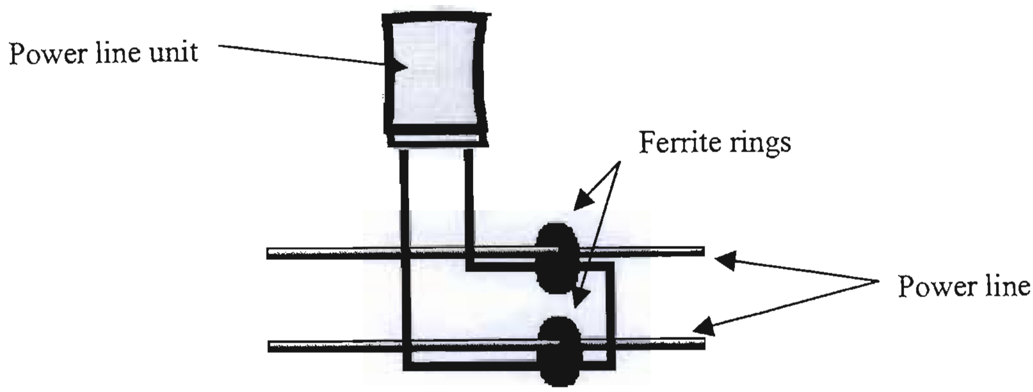

Figure 6.12: Inductive coupling of power line signal to power mains (Source: Ascom [71])

Its advantages are:

- Very good method for coupling points with low impedance,
- Best performance in low impedance situations,
- Results in many cases in lower radiation from power mains than conductive coupling,
- Very simple implementation of multiple coupling points,
- Allows directional coupling to avoid the use of "foreman" installations,
- There is normally no need to switch off electrical power for the installation,
- Easy to install in meter room

With the inductive coupling method the power line signal is injected into the power mains with the aid of Ferrite rings (acting as transformers) and a special signal cable (refer to Figure 6.12). In this case there is no galvanic connection between the power grid and the power line unit. The elements for inductive coupling are:

- Ferrite sets,
- Double insulated twisted pair signal cable,
- Coupling capacitors.

Various ferrite sets are available. The proper choice satisfies the following conditions:

- It is the set with the smallest inner diameter, and

- the maximum current in the mains conductor is smaller or equal to the maximum current specification of the ferrite set.

The coupling capacitors are used to:

- Lower the impedance at the coupling point, resulting in increased coupling efficiency for the inductive coupling method,
- Limit the propagation direction of the inductively coupled power line signal, see Figure 6.13.

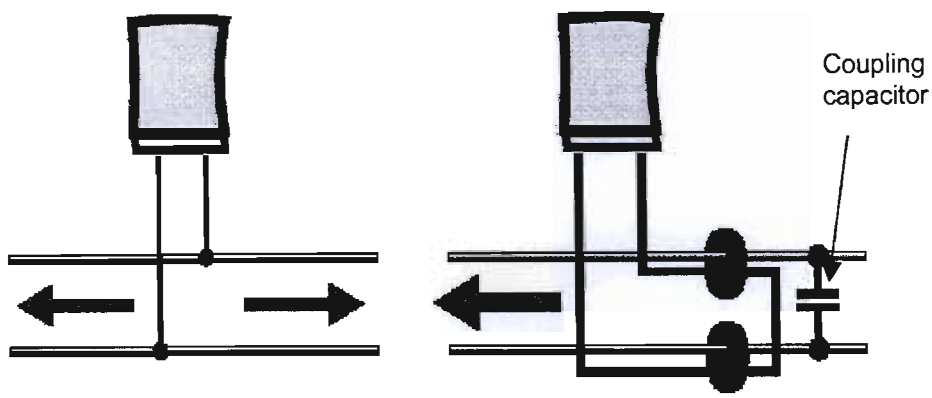

Figure 6.13: Conductive coupling and Inductive coupling with RF short circuit (Source: Ascom [71])

The coupling capacitor forces the inductively coupled signal to propagate in only one direction. Signal propagation direction is shown with green arrows. The coupling capacitor acts like a signal shortcut for the injected power line signal current in the power grid. Therefore the power line signal current will mainly flow through the coupling capacitors and hence will not propagate across this point. For the example in Figure 6.13 the power line signal will only propagate to the left. To achieve the best performance coupling capacitors must be installed as close as possible to the inductive injection point. The capacitor leads must be kept as short as possible. The available power line signal to the right of the coupling capacitor is very low. An attenuation of 20 to 40 dB (depending on the signal frequency and the mains impedances) can be expected. Used properly, this method helps to eliminate the interference between two neighbouring indoor power line systems, thus avoiding the foreman coordination between them.

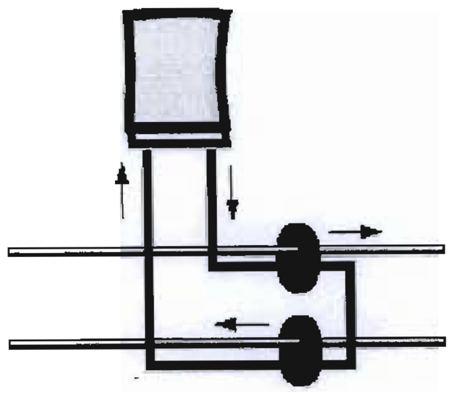

Figure 6.14: Push-pull signal injection (Source: Ascom [71])

The inductive injection must always be installed such that a push-pull signal is generated. The induced signal current must always be flowing in opposite directions in the power mains, as shown in Figure 6.14. The push pull injection greatly reduces the power line radiation from the mains cabling and enhances the coupling efficiency. Push-pull injection produces power line signal currents running in opposite direction in the mains wires.

Special signal cable is used in connection with the inductive coupling method. This signal cable must be twisted and double insulated. The electrical connection of the signal cable is a simple current loop connected to the proper terminals of the power line unit. A simple loop in connection with ferrite couplers can be used to build a very effective signal bridge to step over a lossy installation in the power grid. This installation is purely passive, resulting in low cost and low maintenance. The loss of such a bridge is normally in the range 10 to 15 dB.

6.4 PROPOSED SOLUTION FOR RURAL TELECOMMUNICATION

6.4.1 General

The data that was collected by Statistics SA in KwaZulu-Natal shows that the number of households with public phones at another location (not nearby) is 104,163 and 174,483 households are without telephones (see Table 6.1). The combination of these two groups gives about 280 000 households without *access*. This figure is quite substantial and cannot be ignored. The word "neighbour" in the table refers to a household that is less than a kilometre away. Another location nearby implies a location that is between two to five kilometres away, while another location that is not nearby means any distance above 5 kilometres. There is thus a definite market for more aggressive information access deployment in rural areas.

Telephone Facility	House holds
Fixed telephone and cell phones in dwelling	283316
Fixed telephone in dwelling only	219740
Cell phones in dwelling only	310366
At a neighbour nearby	190731
At a public phone nearby	738306
At another location nearby	65146
At another location not nearby	104163
No access to a telephone	174483

Table 6.1: Rural households with telephone facilities (Source: Statistics SA)

The whole idea of rural telecommunication is to bring to the rural communities affordable information technologies without or very little suffering from the investors in terms of profit gains. Bringing the technology to the people means that the people need to be equipped with the necessary skills. Out of the total population residing in rural areas only a few residents can afford personal computers. Most of the rural residents still need to be equipped with skills required for accessing these services since most of them have never seen these technologies before. The best entry point for the introduction of these services to rural residents is the deployment of these services through telecentres. Telecentres can be placed so that residents do not walk unacceptably long distances to get access. For a starting point in sub-rural areas, these distances should be not more than 2 km to get to the information centre (telecentres, shops, schools, etc.)

The primary objective of many telecentres is to create public telephone access and then introduce a range of other services dependent on this backbone, such as fax, e-mail and Internet/Web access. The minimal set-up for a basic telecentre is usually three lines: one for voice, one for fax and one for Internet access. However, if the PLT is explored there will be no need for many lines as every thing (voice, fax and the Internet) can be sent simultaneously over the single power line and even the energy for powering up the devices can be obtained from the very same line. Provisioning of these services in telecentres will give opportunity for services awareness and training of the residents. In rural areas not only the illiterate people are not familiar with these services, it is still possible to find a well educated person who has never touched a computer. As the people are being introduced to these services, they will see the need and start making personal service requests.

Power line technology can play a major role in the connecting of customers to the telecommunication services. The telecentres, shops and government or tribal offices can be used as central offices. This can cover a lot of end users. From the experimental results that were obtained, it can be seen the end users can have speeds of at least 1.5 Mbps, which is just more that enough for a customer in the sub-rural or rural area. The proposed PLT connectivity is as show in Figure 6.19. This connectivity will use a multi-user adapter as it connects to a large number of customers.

6.4.2 Traffic Consideration

To enable us appreciate the network design requirements in a rural area, surveys were conducted a in certain regions of KwaZulu Natal. This survey focused in the rural areas surrounding Ladysmith (i.e. Emcinseni, St. Chads, Roosbom and KwaNomlebhelele) and also in an area south of Umlazi in Durban known as KwaMakhutha. Figure 6.15 shows the traffic variations on a typical weekday. The figure also shows the traffic during the busy hour. This is very crucial in the sense that it gives a clear indication of loading requirements on the system to be designed, that the bandwidth required must be able to accommodate that maximum traffic. And the network design should be in a way that gives minimal prescribed traffic loss during the peak hour. The traffic was then calculated and it could be aggregated according to the demand.

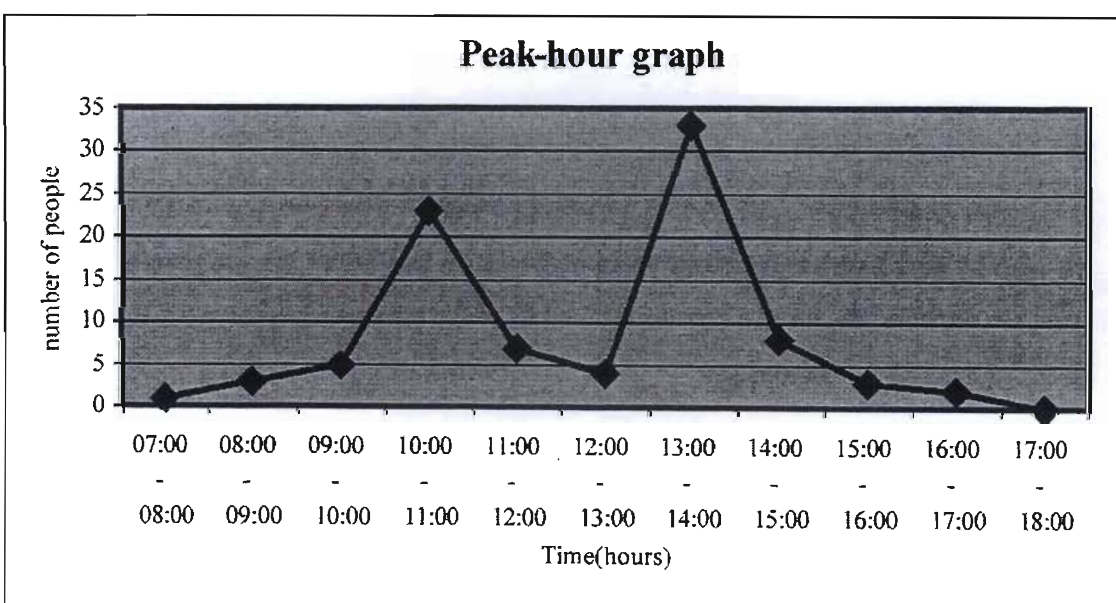

Figure 6.15: Daily traffic variation in a typical rural area

From the traffic variations in Figure 6.15, we can therefore calculate the offered traffic in Erlangs. If the mean holding time (T) is 5 minutes for each caller [73], then the offer traffic can be calculated as follows:

$$\mathit{Offered\ Traffic} = \frac{nT}{t} = \frac{33*5}{60} = 2.75\ \mathit{Erlangs} \tag{22}$$

The offered traffic calculated in (22) is for a single booth. Now given the busy hour traffic (BHT) as calculated above, using the Erlang B charts, with a grade of service of 2%, the number of lines/trunks is found to be 7. If each trunk uses a bandwidth of 64 kbps, 7 trunks will therefore offer a bandwidth of 448 kbps. The throughputs offered by the PLT adapter are quite large (in multiples of Mbps) and they therefore can cater for the BHT without any problems. The problem now lies with the distances between the offices where the master adapters will be connected.

6.4.3 Distance Between Repeaters

Determining the optimum distances is not quite as simple. These vary depending on power output, loss during power distribution, and the noise level at the receiving end. However by applying the results of extensive measurements by Ascom, it is possible to predict the average distance in a concrete situation with sufficient accuracy (see Figure 6.16).

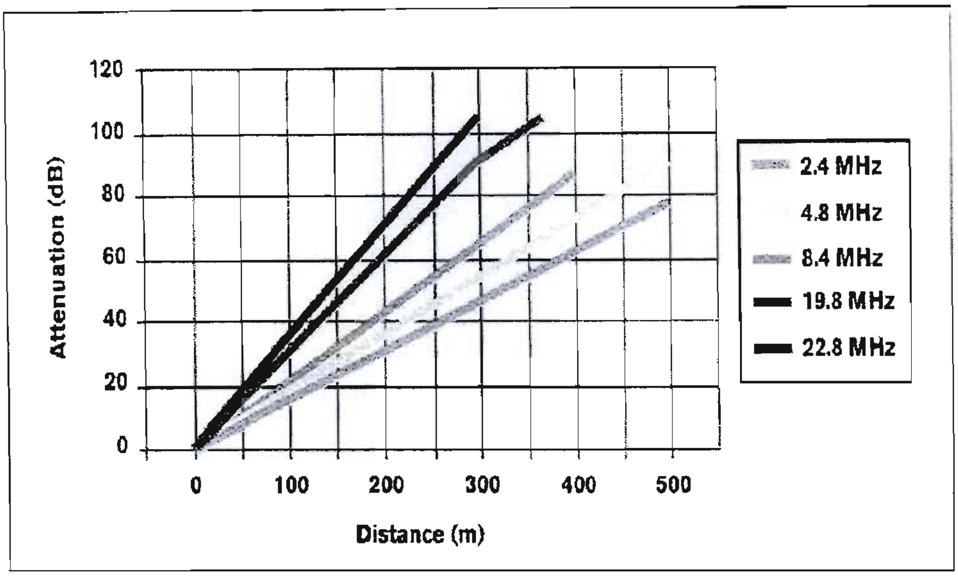

Figure 6.16: Signal attenuation as a function of distance (Source: Ascom [71])

The adapters use 3 carriers in a frequency band of 2-16 MHz with each carrier having a power of 20dBm but only one can be used at full throttle while the others are switched off. If 2 carriers are used then the power of each should be 14dBm and if all 3 are used, then the power should be set to 14dBm for one and 8dBm for each of the remaining two which translates to a total transmit power of 30dBm, one can now calculate the distance at which a repeater can be placed using Figure 6.16. The receiver power is given by:

$$P_r = P_t - P_L(dB) \tag{23}$$

where P_L is power loss on the line, P_t is transmit power and P_r is receive power.

From Figure 4.1 in chapter 4, the power line noise level between 2 - 6 MHz is -50dBV which translates to -33dBm at an impedance of 20Ω. For the signal not to be lost in the channel noise, equation (23) has to hold, where P_n is the line noise power.

$$P_t - P_L(dB) \geq P_n(dBm) \tag{24}$$

From the above equation we can then calculate the signal attenuation as in (25).

$$P_L(dB) = P_t - P_n(dBm) = 30dBm - (-33dBm) = 63dB \quad (25)$$

A SNR of 45 dB gives excellent picture quality for video conferences but for our design we chose 40 dB which is also as good but not perfect. Therefore the minimum received power to give us a SNR of 40 dB is:

$$P_r(\min) = P_n(dBm) + 40dB = -33dBm + 40dB = 7dBm \quad (26)$$

Thus to maintain a SNR of 40dB which is good enough but not the best for e-learning, one needs a received signal level of at least 7 dBm. If the minimum received signal level is 7 dBm, therefore the allowable attenuation margin is:

$$Att(dB) = P_t - P_r = 30dBm - 7dBm = 23dB \quad (27)$$

Referring to Figure 6.16, at 2.4 MHz, the repeater spacing required to give an attenuation of 23 dB is 180 metres while at 4.8 MHz the spacing is approximately 150 metres. The distances between the information centres in rural areas are much larger than these values calculated above. This means that for a distance of 3km, one has to use 15-20 repeaters; this makes the network more expensive to deploy. A typical rural area is shown in Figure 6.17.

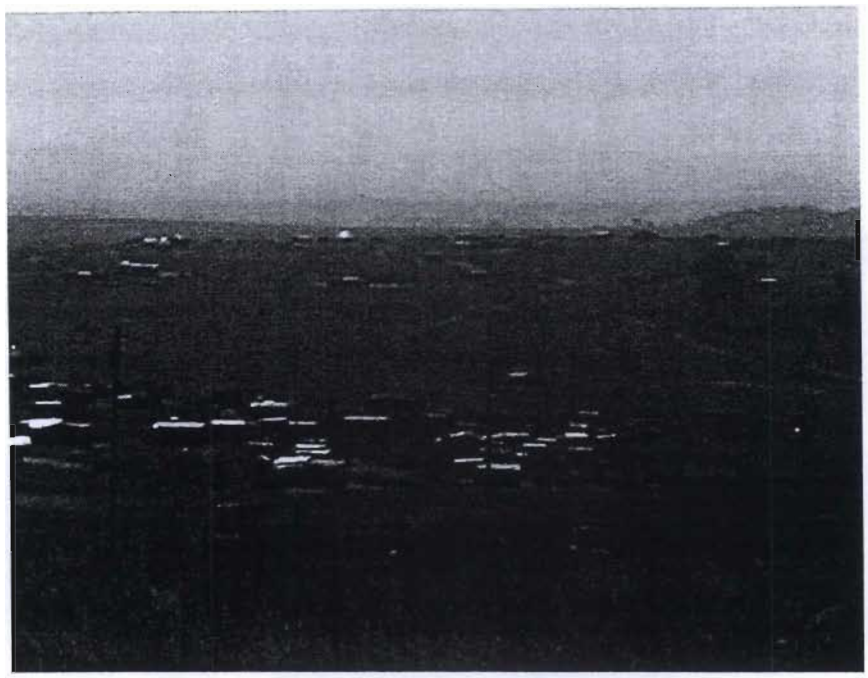

Figure 6.17: Rural area near Ladysmith (Roosbom)

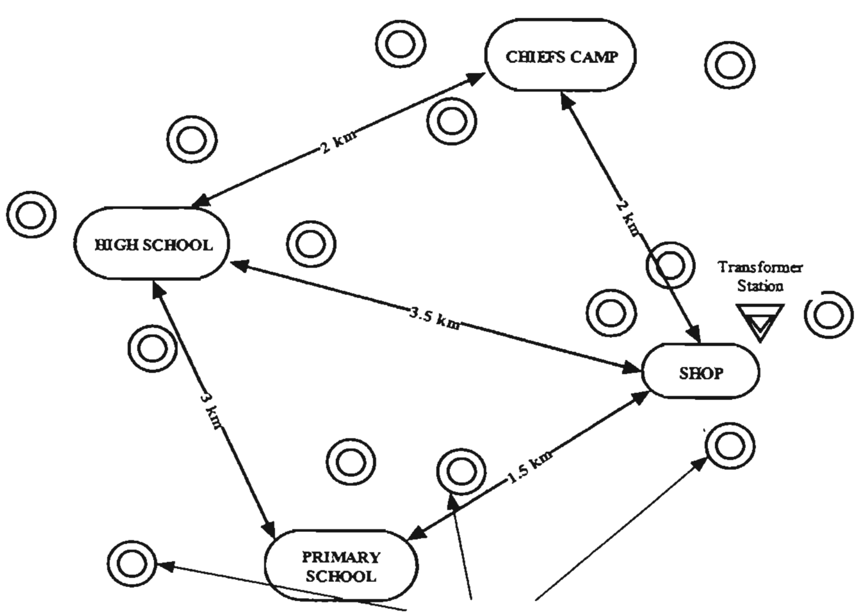

Figure 6.18: Rural layout for Roosbom

6.4.4 Final Solution

Figure 6.17 is a picture of Roosbom which is one of the rural areas surrounding Ladysmith. Figure 6.17 and Figure 6.18 shows a layout of a rural area with every household connected to the power line. The distance between neighbours varies greatly whilst those between large centres can be approximated to a maximum of 3.5 km. If one examines the area in the Figure 6.17 and Figure 6.18, it can be seen that there are a cluster of households around an information centre. With such a layout, one can have houses within a radius of 540 metres connected to the information centre where the connectivity to other centres or the rest of the world will be via a wireless link. This allows the designer to use at most 2 repeaters and in turn reduce the cost of the network. Figure 6.19 shows a proposed connectivity for the households to the information centre.

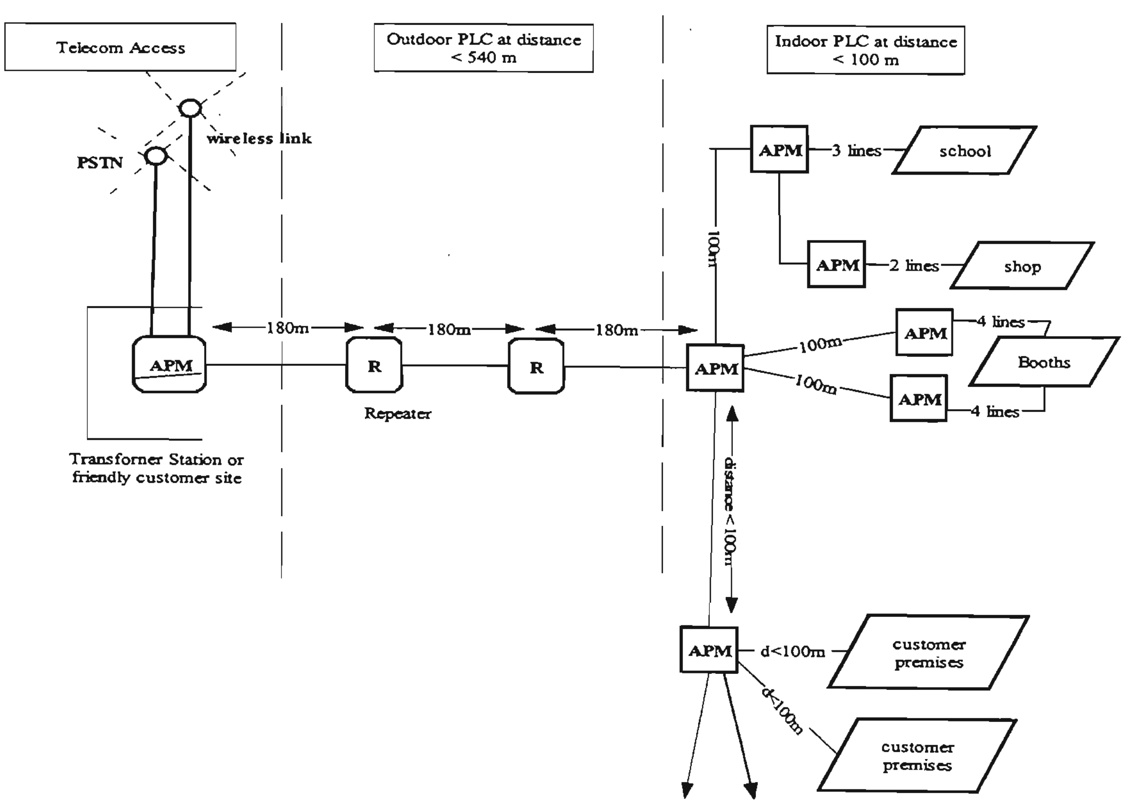

Figure 6.19: Proposed network connectivity for rural areas

The distance can be up to 180 metres without a repeater and if 2 repeaters are used, the distance can be extended to 540m. The distance between customers, which is less than 100 metres, can be regarded as indoor communication and only one master unit can shared. Considering the traffic offered in (22), the proposed number of booth lines is a maximum of 8. The schools and the shop are allocated 3 and 2 lines respectively. Any apartment equipped with a power line modem (APA-45i/o) can either communicate directly with the outdoor master (APM-45o) or with the indoor repeater (APR-30i). The outdoor master provides backbone connectivity with the Internet or the public switched telephony network and controls the repeaters. The master can be located either at the transformer station, or at a friendly customer site (i.e. shops, telecentres, schools, etc.). Reachability can be extended with repeaters in order to achieve extended coverage.

For indoor networks with a number of different interference sources, which in many cases are unstructured, the average values provide no useful indicators since different types of installation affect the transmission distance of up to 100 metres in very different ways. With increasing tests and deployments, reliable estimates can also be produced for indoor systems.

Connecting PLC system into standard backbone architecture generally calls for close collaboration with the network provider and above all concerns aspects of system security, connection of PLC equipment to the network management system. A top-down approach is recommended: beginning with the backbone and proceeding to the outdoor master and access point, down to the adapter inside the building and the required settings on the user's PC.

With the implementation of power line technology rural education centres can now enter the broadband level that allow the students to work more efficiently and convenient when they are learning with computers. With the high speeds offered by PLT, the basic needs such as e-learning and e-health can be achieved. It is the basis for communication platforms to share resources and ideas online between students as well as teachers. In addition it will allow the schools to set up e-learning projects and enhanced information exchange with other institutions in the near future.

The backbone connectivity can be provided via microwave radio links (or PSTN if there is any available) on the roof of each school, telecentre or government office. At the same place the signal is injected to the power grid of the school with an Indoor Master. The 4.5 Mbps modems are in operation for computer rooms where several workstations are sharing the capacity of one CPE (customer premises equipment). The 1.5 Mbps modems are providing access to standalone computers as teacher PC's or student terminals in classrooms.

Subsidising such projects by government can be an effective catalyst in achieving the goal of bridging the gap between the information rich and the information poor. South African government and other African countries have already demonstrated interest towards this goal, through the development of polices that introduce more competition in the telecommunications industry, thus opening a broad platform for the investigation and deployment of cost effective and non existing technologies in the areas that have been neglected for a long time.

CHAPTER SEVEN

7.1 CONCLUSION AND RECOMMENDATIONS

Convergence is a popular term used in relation to the merging of various industrial sectors, made possible by digital technologies such as telecommunications, information technologies, broadcasting, and multimedia. From the above discussion it is clear that the term can be properly used also for the fusion of the energy and information systems. This tendency will have a large impact on the operations of major industrial sectors, i.e. power utilities, commercial/residential information product users, and technology/application suppliers.

While in industrialised countries the traditional telecoms infrastructure achieves a penetration approaching 100%, in semi-peripheral regions, and even more so in developing countries, a dramatic lack of infrastructure exists. In contrast to traditional access links, the electricity supply infrastructure covers about 40 % of the rural population in South Africa. Therefore a great number of households can be connected using power line communications. Power is available everywhere. PLC communications achieves two-way broadband bandwidth for all connected households because PLC only has to cope with a few 100 metres distance, while DSL has to bridge around 4.5 kilometres of copper wire. Therefore traditional broadband links such as cable and ADSL are not available to a large part of the rural population, power lines connect more people.

In the process of bridging the gap between the "*Information rich*" and "*Information poor*", this thesis has proposed the power line network as a communication medium, which is based on OFDM to be used for the purpose of providing the telecommunication services and hence overcoming the deficiency in telecommunication services and combat the hostile environment which prevail in rural areas. The idea of using the power line grid as the core networks is to explore its advantages and strength in terms of coverage, capacity, easy of operation and maintenance, which are sorely embedded in these systems. This network can provide a common format for communication that can support all services and can be supported on various transmission systems.

In this work, power line communication systems employing OFDM are described and compared. Channel information is assumed not to be available at the transmitter side. Both the situations with and with no channel information at the receiver are regarded. In order to make a general analysis possible a stochastic power line channel model is introduced. Incorporating the transmitter and receiver operations of OFDM into the model and using coding across the OFDM–sub carriers, a slowly time–varying frequency non–selective fading channel is obtained. The capacity of this fading channel is calculated for the cases of coherent transmission and differentially encoded transmission with multiple symbol differential detection.

The numerical results of the channel capacity show that the frequency dependent signal attenuation and the transmission bandwidth largely influence the required average signal–to–noise ratio for reliable communication at the receiver. To combat the signal fading the application of large signal constellations and low rate codes proves to be convenient. According to the capacity curves the perfect knowledge of the channel characteristic leads to considerable gains of the order of some dB in the signal–to–noise ratio. Increasing the observation interval of the noncoherent detection can reduce the gap between transmission with and with no channel state information at the receiver.

The theoretical results derived from capacity analysis are affirmed by means of simulations for 8PSK and 16QAM signal constellations. As well–known for transmission over fading channels, the interleaving depth is required to largely exceed the coherence bandwidth of the fading process along the frequency axis. The practical results show that power lines can be used as a communication medium. In terms of the practical experiment, we can not report on distance as one of the factor that makes high speed wire line communications a problem. Looking at the proposed network layout, customers in sub-rural areas closer to the central office can get access speeds in several Mbps and as the distance from the central office increases, the speed will decrease. Another problem which is the line noise can be taken care of since the power line units uses regulated communication similar to fax. As the line noise increases the power line units will automatically regulate the speed at which they can communicate well.

At present, ADSL is offered to South Africans at a speed not more than 512 kbps if within the reach of about 4 km and if the line is tested for good quality. South Africa is a broadband laggard when compare to countries such as Japan, Korea, Denmark and Iceland. One of the many reasons is the cost of rolling out new broadband technologies. The South Africans are paying between $70 to $100 per month for a ADSL connection while Americans typically pay $40 to $50 monthly for a ADSL or cable modem connection, the Japanese, for example, pay $10 to $15 a month for even faster connections [74]. This means that South Africans are paying more for less.

The appeal of power line technology is that most of the wiring for the network is in place which minimises the cost of rolling out new wires. Although data must be carefully routed over the electric grid to prevent interference and signal degradation, there is no need to dig up streets or rewire homes. It is also a compelling choice when it comes to speed as compared to the other existing technologies. The major technical challenge has been how to send bursts of radio frequency energy over power lines without interfering with other radio signals, particularly ham radio and public safety frequencies.

Although this is a very good network in terms of coverage, capacity, ease of operation and maintenance, we recommend this network for sectors of rural telecommunication that require medium bandwidth. Due to the short distance between repeaters, the trade – off between bandwidth and distance becomes a major design issue. As rural areas can be subdivided, this work is recommended for the fast developing rural areas or sub-rural areas since the distance between neighbours is not that large. For the areas that are slowly developing, this technology can not be apply to them since they do not have electricity in their back yard; and if they had electricity, the distance will still play a major role in hindering the information services being brought to the rural community which is sparsely distributed. In this case, wireless access is a better option.

7.2 FUTURE WORK

An investigation should be launched to investigate the technology that uses microwave technology to pull data through the magnetic field created by alternating current flowing through the electrical power grid. The South African electric power system operates at 50 cycles a second or hertz. This means that the electric charges or current flowing in the system changes direction 50 times every second. The alternating current is what causes the radiation of the magnetic field that surrounds the electrical wires. Electric fields are easily shielded or weakened by conductive objects but magnetic fields are not. Modulating signals onto the magnetic field, instead of the electrical field, is what makes it possible to transmit signals through transformers, over high voltage electrical transmission (500 kV) and distribution (11 kV) lines, at speeds up to 2.5 gigabits per second.

Microwave signals propagated onto the magnetic flux field can travel up to 3000 kilometres without regeneration. The process writes telephone, radio, video, Internet and satellite data within the magnetic wave by using proprietary software and hardware. This allows the electrical grid to carry these communications services at near light speed. This develops a low cost, reliable means of transmitting data, voice and video at high speeds. The distances covered by this technology look very attractive for long distance reach which is one of the greatest problems in rural telecommunication.

Working on a medium-voltage network can bring a better coverage with enough bandwidth. An ambitious initiative to bring to the PLC community a wide range of PLC products enabling customers to provide a rich bouquet of services and delivering the promise of the third pipe to the home at a low cost of ownership results in a need for medium voltage products.

DS2 Wisconsin technology has developed its next generation (2G) broadband PLC access system. The data rates that these chips can provide are up to 205 Mbps. The latest power line product family member (API-2000-MV) is a result of synergy between the technically proven Wisconsin chipset from DS2 and the industry wide acknowledged leadership in system design, industrialization and deployment aspects. The medium voltage technology is expected to provide a much higher performance and will be available at lower prices.

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APPENDIX A

Part 15 of the FCC Rules applicable to Power Line Systems

Current Carrier Systems

15.107 Conducted Limits–

This section sets out the conducted limits of devices connected to the AC mains supply.

15.107(a) Limits for all devices except Class A digital devices and the current carrier systems in part (c).

Frequency (MHz)	Quasi-peak (dBmV)	Average (dBmV)
0.15-0.5	66 to 56	56 to 46
0.5-5	56	46
5-30	60	50

15.107(b) Limits for Class A digital devices

Frequency (MHz)	Quasi-peak (dBmV)	Average (dBmV)
0.15-0.5	79	66
0.5-30	73	60

15.107(c) Current Carrier Systems
The limits shown in paragraphs (a) and (b) of this section shall not apply to current carrier systems operating as unintentional radiators on frequencies below 30 MHz. In Lieu thereof, these current carrier systems shall be subject to the following standards:

1) For current carrier systems intended to be received using a standard AM broadcast receiver.
2) For all other current carrier systems within the frequency band 535-1705 kHz 1000 mV.
3) Carrier current systems are also subject to radiated emission limits.

15.107(d) Measurements to demonstrate compliance

15.109 Radiated Emission Limits

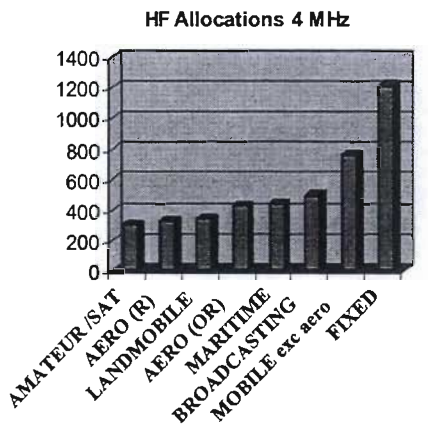
15.109(a) Limits for all devices except Class A digital above 30 MHz
15.109(b) Limits for Class A above 30 MHz
15.109(c) Band edge values
15.109(d) CB receivers
15.109(e) Current carrier systems are subject to the radiated limits in 15.209 between 9 kHz and 30 MHz.
15.109(f) Receiver terminals
15.109(g) Acceptance of devices which comply with CISPR 22

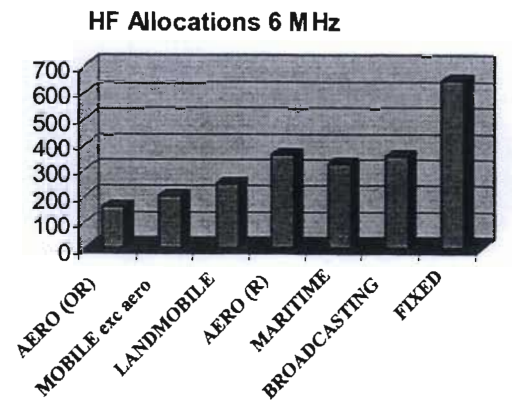
15.209 Radiated emission limits, general requirements

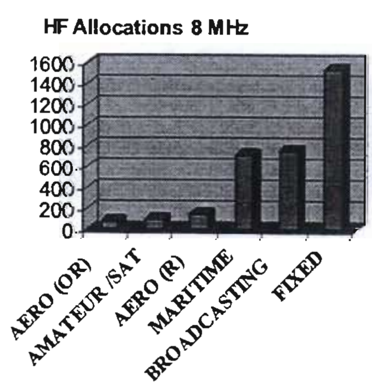
Frequency(MHz)	Field Strength(uV/m)	Measurement Distance
0.009-0.490	2400/ F(kHz)	300
0.490-1.705	24000/ F(kHz)	30
1.705-30.0	30	30
30-88	100	3

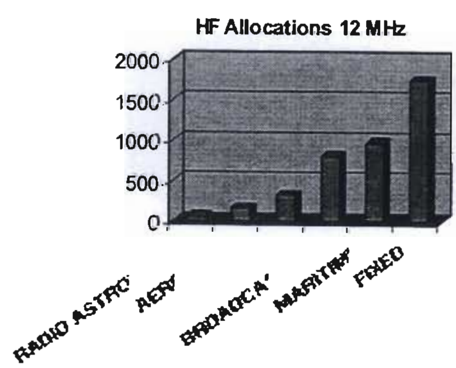
APPENDIX B

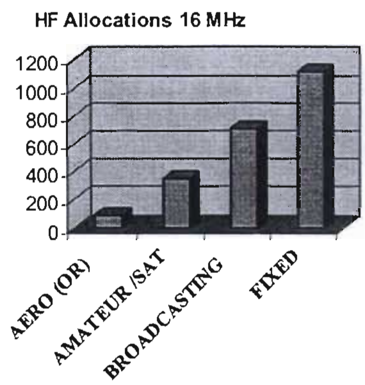
Frequency Allocation







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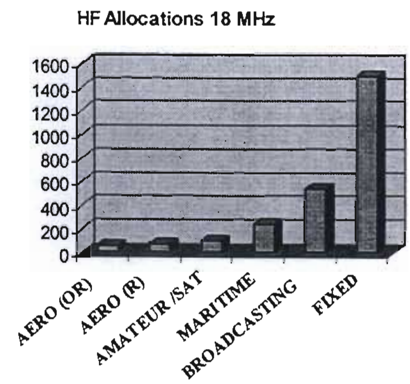
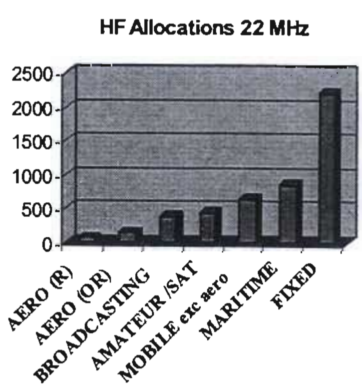
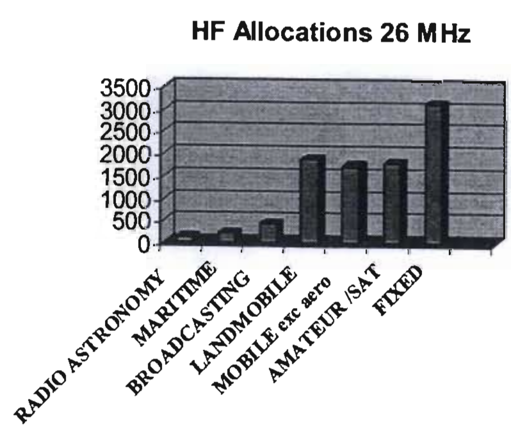
1200
1000
800
600
400
200
0
AERO (OR)
AMATEUR /SAT
BROADCASTING
FIXED


HF Allocations 18 MHz
1600
1400
1200
1000
800
600
400
200
0
AERO (OR)
AERO (R)
AMATEUR /SAT
MARITIME
BROADCASTING
FIXED


HF Allocations 22 MHz
2500
2000
1500
1000
500
0
AERO (R)
AERO (OR)
BROADCASTING
AMATEUR /SAT
MOBILE exc aero
MARITIME
FIXED


HF Allocations 26 MHz
3500
3000
2500
2000
1500
1000
500
0
RADIO ASTRONOMY
MARITIME
BROADCASTING
LANDMOBILE
MOBILE exc aero
AMATEUR /SAT
FIXED

APPENDIX C

The currently proposed limits for PLC interference field strengths

1. NB30.

Frequency Range MHz	(Peak) Disturbance Field Strength Limit dB(μV/m)	Measurement Distance	Measurement Bandwidth
0.009-0.15	40-20*log f (MHz)	3 metres	200 Hz
0.15-1	40-20*log f (MHz)	3 metres	9 kHz
1-30	40-8.8*log f (MHz)	3 metres	9 kHz

2. Norwegian proposal.

Frequency Range MHz	(Peak) Disturbance Field Strength Limit dB(μV/m)	Measurement Distance	Measurement Bandwidth
0.15-1	20-20*log f (MHz)	3 metres	9 kHz
1-30	20-7.7*log f (MHz)	3 metres	9 kHz

3. BBC proposal.

Frequency Range MHz	(Peak) Disturbance Field Strength Limit dB(μV/m)	Measurement Distance	Measurement Bandwidth
0.15-30	21.8-8.15*log f (MHz)	1 metres	9 kHz

CISPR 22 B, limit for mains disturbance voltage, measured at the 230 V mains terminal of ITE apparatus classe B, intended for use in residential areas.

Frequency Range MHz	Quasi Peak Disturbance Voltage limit dB(μV)	Average Disturbance Voltage limit dB(μV)	Measurement Bandwidth
0.15 - 0.5	66 - 56	56 - 46	9 kHz
0.5 - 5	56	46	9 kHz
5 - 30	60	50	9 kHz