COST EFFECTIVE DSL SOLUTIONS FOR THE DEVELOPING COUNTRIES

By

Zwelandile Mbebe

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Supervisor: R Sewsunker

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Abstract

Developing countries in Africa present a graphic picture of the digital divide. High costs associated with serving rural customers are the major cause of uneven distribution of services. Rural areas are characterised by a high rate of unemployment and a poor level of education. This results in a scenario where most of the residents are unable to utilize IT resources. Some people in these areas are not informed about the availability and importance of these technologies in the market. Those who are academically fit for accessing these technologies often cannot afford them. Some of the areas still have no existing telecommunications infrastructure. High deployment costs associated with broadband services makes it even more challenging to deploy such services in this environment.

In Africa approximately 80% of the population is living in rural areas, which alone creates a demand for the coverage of rural regions. Leaving such a large number of residents not connected, means poor medical care, students cannot participate in distance learning programs which means poor quality of education, poor performance in businesses, poor farming and crippling delivery of government services.

DSL technologies were originally designed to suit suburban to urban conditions. In this research it is shown that broadband services can be delivered to rural people by applying DSL technologies, using the existing telecommunications infrastructure. This will mean significant savings, as it does not need core network investments. DSL increases network capacity to a network, which is no longer limited to voice. With this technology a number different high bandwidth applications are delivered to the homes, schools, hospitals, telecentres and small businesses.

The cost effectiveness of these technologies for several reach and rural traffic environment is investigated. This is done by investigating several promising DSL solutions in terms of diverse geography, demographics and other cost dictating parameters.

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This work is dedicated to all the physically challenged students in Westville campus.

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Abbreviations

A

ADSL	Asymmetric Digital Subscriber Line
AMI	Alternate Mark Inversion
AN	Access Node
ANSI	American National Standards Institute. Accredits and implements
ATM	Asynchronous Transfer Mode
ATU-C	ADSL Transmission Unit - Central Office
ATU-R	ADSL Transmission Unit - Remote
AWG	American Wire Gauge
AWGN	Additive White Gaussian Noise

B

BER	Bit Error Rate
BRI	Basic Rate Interface
BT	Bridged tap

C

CAP	Carrierless Amplitude & Phase Modulation.
CAP	Competitive Access Provider
CAT5	Category 5
CLEC	Competitive Local Exchange Carrier
CO	Central Office
CPE	Customer Premises Equipment
CSA	Carrier Serving Area

D

DDS	Digital Data Service
DHCP	Dynamic Host Configuration Protocol
DLC	Digital Loop Carrier
DMT	Discrete Multi Tone

DSL	Digital Subscriber Line
DSLAM	Digital Subscriber Line Access Multiplexer
DTE	Data Terminal Equipment
DWMT	Discrete Wave Multi-tone
E	
EC	Echo Cancelled
EO	End Office
ETSI	European Telecommunications Standardization Institute.
F	
FDDI	Fiber Distributed Data Interface
FDI	Feeder Distribution Interfaces
FDM	Frequency Division Multiplexing
FEXT	Far End CrossTalk
FSAN	Full Service Access Network
FTTC	Fiber To The Curb
FTTcab	Fiber To The Cabinet
FTTH	Fiber To The Home
G/H	
GUI	Graphical User Interface
HDSL	High-bit-rate Digital Subscriber Line
HDSL2	Second Generation High Bit Rate
HDTV	High Definition TV
I	
IDSL	ISDN DSL
IL	Insertion Loss
ILEC	Incumbent Local Exchange Carrier
IP	Internet Protocol
ISDN	Integrated Services Digital Network
ISP	Internet Service Provider
ISI	Inter Symbol Interference

ITU	International Telecommunications Union
L	
LAN	Local Area Network
LEC	Local Exchange Carrier
M	
MAC	Media Access Control
MDF	Main Distribution Frame
MDU	Multiple Dwelling Unit
MPEG	Motion Picture Experts Group
MPLS	Multi-protocol Label Switching
MUX	Multiplexer
N	
NAP	Network Access Provider
NEXT	Near End CrossTalk
NSP	Network Service Provider
NTU	Network Termination Unit
O/P	
ONU	Optical Network Unit
PAM	Pulse Amplitude Modulation
PBX	Private Branch Exchange
POP	Point-of-Presence
POTS	Plain Old Telephone Service
PPP	Point-to-Point Protocol
PSD	Power Spectral Density
PSTN	Public Switched Telephone Network
PVC	Permanent Virtual Circuit
Q/R	
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RADSL	Rate Adaptive DSL

RD	Resistance Design
RDD	Revised Resistance Design
RFI	Radio Frequency Interference
RTU	Remote Terminal Unit
S	
SDSL	Symmetric DSL
SHDSL	Single Pair-High-Bit-Rate Digital Subscriber Line
SM	Spectrum Management
SOHO	Small Office/Home Office
SONET	Synchronous Optical NETwork
SVC	Switched Virtual Circuit
T	
TCP/IP	Transmission Control Protocol/Internet Protocol
TDD	Time Division Duplexing
TDM	Time Division Multiplex/Multiplexer
TELCO	Telephone Company
U	
UBR	Unspecified Bit Rate
UNI	User to Network Interface
UTP	Unshielded Twisted Pair
V	
VBR	Variable Bit Rate
VC	Virtual Circuit
VDSL	Very-high-bit rate DSL
VOD	Video On Demand
VPN	Virtual Private Network
W/X	
WAN	Wide Area Network
xDSL	Refers to all DSL-based services

#

10Base-T	A 10 Mbps Ethernet LAN that works on twisted-pair wiring
100Base-T	A 100 Mbps Ethernet LAN that works on twisted-pair wiring
2B1Q	Two Binary, one Quaternary

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Chapter 1

Introduction

1.1 Broadband Networks

A number of different definitions for broadband technologies exist. Out of these definitions there is no standard definition, the reason being the changing parameters which these definitions use when defining broadband. Broadband is always associated with the current highest transmission speeds. Since the technology is advancing every day, these speeds are also changing rapidly. The most used definition is proposed by the ITU (ITU Rec. I.113).This definition considers any network that is transmitting at data rates greater than 1.5Mbps or 2 Mbps as a broad band network [1]. Broadband technologies are designed to fit particular conditions. This results in a no broadband solution that can fit all the countries. Countries differ in economic, cultural, political, geographical and other technology choice dictating factors. The broadband technologies are divided into two transmission medias; these are wire line and wireless transmission medias, with both medias having a number of different technologies.

1.2 Drivers for Broadband Networks

Evolution of networks demands that service providers utilise up to date technologies, which can only be achieved by upgrading or replacing the existing networks. This includes increasing speeds of LANS, integration of voice, data, video and other network evolutions. Service providers also have business interests in broadband networks. In this case the key issue is the payback period on the deployed services. The provisioning of multimedia services mean the allocation of higher bandwidth to the customers, which is always accompanied by increased revenues. Integrating multiservices within a single network also means significant savings on the service provision. Integrated networks can multiplex a number of connections on small number of broadband links, which means an increase in the number of customers, thus increased revenue. Service providers always stick to technologies that can reduce capital costs required in supporting and maintaining the deployed services.

1.2.1 Customer Demands

Broadband connectivity drives innovation in personal communications, education, business, government and medicine. In all these cases a customer is not interested in what it took the service provider to deliver the services, but only interested on the price and quality of the services. At the same time customers will always demand new advanced services like fast Internet downloads, desktop video conferencing, interactive television, multimedia mail, teleshopping and telebanking. Some of these demands arise in the customer daily applications, since some of these customers use these services for business purposes.

1.2.2 Government Intervention

Difficulty in providing services to rural areas is mostly related to returns on investments. DSL deployments in developed countries have typical payback periods of 4- 8years. This gives an indication that in developing countries this period can be even longer. Rural residents are low revenue generating customers. As a result, telecommunications service providers are less attracted in investing in these areas. Connecting a subscriber means investing approximately 50 percent of the resources only on the access. Average subscriber connection costs in rural areas are several times higher than connecting an urban subscriber. If only revenues are considered, the wire based telecommunications services cannot be provided to rural residents. Rural subscriber connection should be done with the purpose of improving the quality of the rural residents. This can be catalysed by government, through encouraging telecoms service providers and subsidising the rural connection. The South African Government has developed programs that are encouraging and equipping society with skills like use of Internet. Telecentres have been established in order to avoid leaving out those who can't afford their own personal computers. The government has also been active in promoting Internet use in education sectors. Some schools have been sponsored by different computer manufacturers with computers, through the help of government. This makes it easy for students to access information from anywhere in the world. Students are also given chances for playing games which can help them to improve their thinking, judging and decision making skills.

1.2.3 Broadband Equipment Vendors

During the early deployments of DSL, the DSL equipment was expensive. This was because of the limited number of manufacturers of DSL equipment. In due course with more companies getting interested in DSL technologies, the vendor competition is increasing. High business competition is always accompanied by a drop in prices and better service quality.

1.3 Broadband Networks Technologies and Elements

A broadband network is made of two elements; these are the access and the core network. There are a number of different kinds of both access and core network technologies.

1.3.1 Broad Band Access Technologies

The broadband access technologies consist of the following:

- xDSL, which means a variety of DSL technologies
- Cable modems
- High-speed wireless (3G), radio, satellite
- Wireless: 802.11b (WiFi), Bluetooth
- High-speed LANs
- Gigabit Ethernet and switched Ethernet

Figure 1.1 shows the distribution of these broadband access technologies in 2002. According to ITU world telecommunications indicators data base, in 2002, DSL was estimated at 59 percent of the broadband technology followed by cable at 39 percent and others making 2 percent [2]. This is because of a number of advantages of DSL against other access technologies.

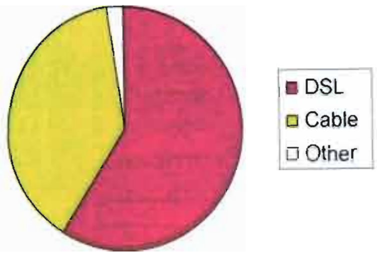

Figure 1.1: Distribution of broadband access networks 2002

1.3.2 Core Network Technologies

The broadband core technologies consist of the following:

- Fibre transport
- Photonic multiplexing and switching
- ATM multiplexers, switches, and routers
- Wire-speed router
- MPLS switches

1.4 The Digital Divide

There is a very wide gap between the telecommunications facilities of developing countries and developed countries. In 2000, ITU approximated only two telephone lines per hundred people in Africa, compared to four lines per ten people in Europe. The average distance between phones in rural Africa was approximated to be 50 kilometres. Europe had a penetration rate of 60 percent [3]. After the year 2000, telecommunications infrastructure has increased at higher rates because of the developments. In South Africa telecommunications infrastructure is even expected to increase more than any other country between 2004 and 2010, because of the responsibility of hosting world cup in 2010. So far developments in telecommunications infrastructure have been concentrating more only on voice services. This is witnessed by the number of mobile phone users that are found in rural areas. In January 2002 there were about 11, 2 million cellular users in

South Africa. This number was expected to increase to 21million by 2006 [4]. In Africa as a whole, South Africa is amongst the countries that have shown a high growth rate in mobile users. Most of the people residing in rural areas are happy with having an access only to voice services, through their cell phones. The reason is that most of the residents are not aware of any other available IT service. A number of researches that have been done show that there are many challenges associated with deploying DSL in countries with long loops. Some have declared that DSL is an inappropriate technology for rural areas. This can lead to the conclusion that there is no hope for successful DSL deployments to regions like Africa, which are 80 percent rural. People residing in rural areas are more likely to be scattered, which means a low population density. The residents here are faced with a problem of being isolated from accessing services and goods. These areas consist of settlements, villages, and small towns and can extend up to few hundred kilometres from an urban or city centre. The distances between the residents and the Central office are much greater than a well known DSL range of 5.5km. This alone creates a demand for the investigation of methods of extending the DSL reach. Some of the rural areas still rely on solar energy for power supply, since they are not electrified. Another complex issue on addressing rural telecommunications is the diversity in the definition of a rural area. There is no single definition of a rural area, which results in no single solution for rural areas. Different unique characteristics of rural areas in terms of demographics, climates, terrain, cultures and other cost dictating parameters need to be considered. This has to be done in order to come up with a suitable specific solution for each scenario. Successful rural broadband deployment relies on solutions designed to meet individual community's needs, not a one fit all solution. Topographical conditions are the major obstacle to the construction of conventional lines and transmission systems. In this study a number of topographical rural situations are going to be studied. All these factors contribute to the existing dilemma of investing on broadband technology in rural areas. Topographical constraints lead to high costs of wire based infrastructure, leading to a threat of leaving the rural areas not wire line connected. Although that is the case, the presence of these challenges does not mean that there are no opportunities for broadband services in the rural areas. All it means is the challenge for coming up with cost effective and advanced engineering skills for providing these services. Government policies can also play a big role in catalysing the broadband deployment process. The introduction of competition in the telecommunications industry adds a great value towards the goal of rural coverage. Competition results in different companies providing different technologies at different competitive costs. This means the investigation and provisioning of cost-effective solutions, designed to meet the customer interests.

The major goals for connecting the rural residents can be summarised as follows:-

Connecting a rural subscriber means

- Improvement in the quality of education through distance learning programs and video conferencing lessens
- Efficient utilisation of medical resources trough telemedicine services
- Unlocking the talents of the people that were never given a chance to participate and benefit from global information
- Better performance of businesses and farmers located in rural areas
- Immediate access to assistance during civil wars and natural disasters.

1.5 DSL Market Penetration

The African region is far behind in deploying DSL technologies compared to the other regions. According to the world DSL statistics, in December 2003 there were about 41.4 million DSL lines deployed worldwide with a growth rate of 15.2%, calculated between December 2002 and March 2003 [5]. Asia-Pacific was leading with 16.4 million lines, followed by Western Europe with 11.3 million lines, followed by North America with 8.7million lines, followed by the combination of South East and Asia by 3.5 million lines, with the rest of the world taking 1.4 million. Middle East and Africa had 0.2 million lines with a growth rate of 34.8%. This makes only about 0.57% of the total deployed DSL lines in the world. Of this Israel owns 86% of DSL lines, and UAE holds 8.6%, which means a total of 95%. The other countries fall in the remaining 5%. Assuming the constant growth rate for the total world lines and "Middle East and Africa", the following equation can be used to approximate the number of deployed lines in March 2004.

$$Y_{n+1} = Y_n + (Y_n \times G_r) \qquad (1)$$

Assuming the constant growth rate G_r, Y_n is the number of DSL lines and Y_{n+1} is the number of DSL lines in the next period of three months. After four iterations it is found that in March 2004 there were about 72.8 million deployed DSL lines worldwide, with Africa and Middle East having 0.8 million, which means 1.1% of the deployed worldwide DSL lines. Figure 1.2 shows the top ten DSL countries per 100 population.

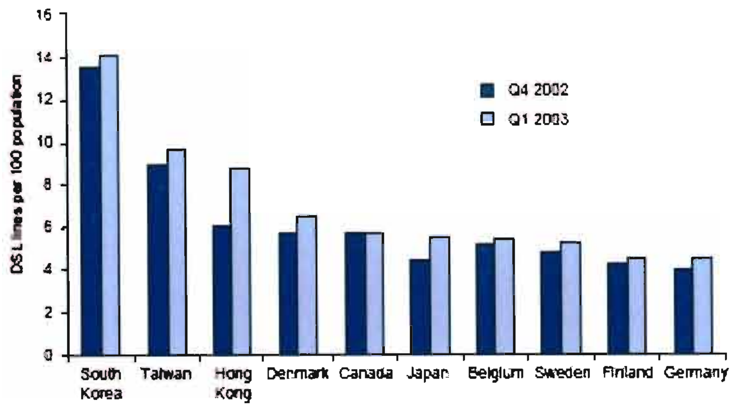

Figure 1.2: Top Ten" countries for DSL penetration per 100 population [5]

In Africa, the question of affordability remains a problem. This is due to the high unemployment rate amongst the rural residents. Most of these people are poorly educated, with some being completely illiterate. The most potential broadband customers here are farmers, government sectors and businesses such as hotels and nature reserves. African rural areas are very attractive to tourists. These people would like to have an access to these services during their times of visit. Some of these tourists are business people and would like to do some work while enjoying themselves.

1.6 Rural Traffic Patterns

Because of the diverse definitions of rural areas, this section defines the common scenarios that are found in African rural areas. These resident patterns are the major cost dictating parameter in DSL deployments. In order to ensure cost effective deployment, each scenario has its own unique solution.

1.6.1 Village/Single Town

These are towns that are usually found as far as 200 km from the urban centre. These towns have an average diameter of 2- 4.5Km.The average service demand is between 300 to 1000 subscribers, with a demand density of 60-70 subscribers per square kilometre. The resident patterns here are more likely to be clustered. Figure 1.3 shows a typical clustered pattern of residents.

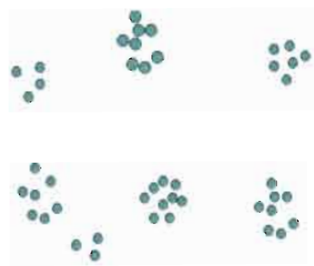

Figure 1. 3: Clustered Pattern

These patterns are the result of subscribers residing around the schools or hospitals. Most of the residents here are potential customers. The reason is that some of the customers here are clinics, hospitals, schools and other governmental structures. Each central office here serves a particular cluster with reasonable number of subscribers.

1.6.2 Widely Scattered Areas

Figure1. 4 shows an example of widely scattered residents.

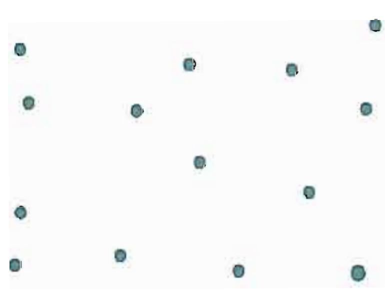

Figure 1. 4 : Distributed pattern

These areas are characterized by a very low population density. Good examples of such areas are farms and people residing along the mountains. This is the most difficult pattern to deal with when providing DSL services. This pattern demands more central offices with each central office serving very few customers. These have got an average diameter of 10-40Km.The service demand is between 300 and 1000 subscribers, with a demand density of 4-16 subscribers per square kilometre.

1.6.3 Belt Pattern

Figure 1.5 shows a typical belt pattern scenario.

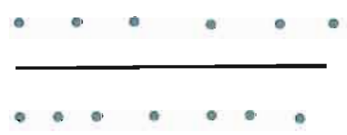

Figure 1.5: Belt Pattern

This pattern results from the villages located along the roads or riverbanks. These are characterized by the average service demand of 100-300 subscribers, with a demand density of 20-30 subscribers per square kilometre in each town.

1.7 A Typical Rural Network

Copper is one of the existing network infrastructures in the rural areas. In some areas copper has been replaced by wireless network technologies because of problems associated with vandalism and theft of copper. In South Africa, existing loop plant does not have load coils. That means copper has been deployed over short distances from the central office. This will be discussed in more details under loop qualification. The other reason for removing copper in some areas is the average cost of connecting a rural subscriber to the central office, and high maintenance costs. This ranges from R3300 to R5500 per line. Considering maintenance costs and low subscriber density, this price can increase to anything above or equal to R7000. The existing rural network has been designed following the electrical characteristics of the copper pairs, within the local loop. This has forced the telecommunications service providers to consider only the customers that are within 10 to 15 km from the central office. In areas with very low population density that means some central offices will serve as few as 16 lines. Central offices have been placed such that a large number of customers are located very close to the central office. The population density decreases with the increase in the distance from the central office.

Figure 1.6 shows a typical rural access network. This architecture will be discussed in more details on Chapter 3.

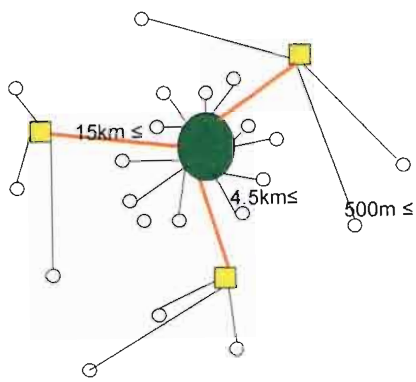

Figure 1.6: Typical rural copper network

1.8 Rural DSL Deployment Issues

The deployment issues here are not substantially different to those experienced in urban areas. The main advantage in urban areas is the number of potential customers to be found in an area, which makes it easy to determine the revenue per user. This has resulted in digital subscriber line multiplexer (DSLAM) manufacturers to produce DSLAMs with a high number of pots in order to reduce the cost per user of expensive backhaul connections and network switches. These DSLAMs were designed to be housed in the Central Office Exchanges in typical clean and air conditioned environment. In rural areas the issue is the same but the design philosophy is different. Rural areas do not provide a high number of subscribers that can be crammed in a single large capacity DSLAM. Large capacity DSLAMs designed for urban central offices will be too expensive when shared between low volumes of users. This results to a need for another approach for low-density customers.

1.8.1 Equipment Costs

In many of the developing countries, the fixed infrastructure is often based on analogue systems, which need to be replaced by digital systems. Before service providers offer a service to customers they need to have purchased and installed the hardware-Customer Premises Equipment (CPE) and Digital Subscriber Line Access Multiplexer (DSLAM) equipment. It is this equipment that connects the customer to the backbone network. These costs for ATM and IP based DSL on a price per port basis are similar, but the total cost of ownership for the network and equipment, including backhaul interface costs are 30-50 percent lower in a pure IP based DSL. The savings in equipment costs are primarily because of the price of the backhaul interface and ATM switch connection to the network. The cost of interface port on an ATM switch and the cost of a private virtual connection (PVC) grooming device become significant outlay in large infrastructure .An IP switch/router to connect to the Internet is required. The interface for these to connect to the ATM infrastructure is expensive.

1.8.2 Reducing Backhaul Costs

Either direct fibre link, or wireless or even a copper backhaul needs to be provided from the local point of presence to the core network. Typically in DSL deployments this link has been a Gigabit Ethernet port. This means that with an ATM based DSLAM architecture this connection is either 155Mbps and therefore a large costly pipe, or it involves a conversion of the traffic from ATM cell formats to Ethernet frame formats, a conversion that is expensive in terms of power consumption at the unit as well as the hardware costs and the unit size are all important considerations in a rural deployment.

1.8.3 Maintenance and Upgrades Costs

The main concern here is trouble shooting and fault finding within the network. This is a very important factor as it is the one that determines maintaining the customers. In order to ensure short payback periods, deployment has to be made in a wide geographical area in a short period. The provider's response to a service request must be rapid in order to maintain the customer's interests. This can be done cost effectively by making sure that the Customer Premises Equipment (CPE) is kept as simple and easy to deploy as possible. The start-up configurations also need to be user friendly. Costumer waiting time has to be kept short at the central office. Customers may get irritated if there are delays in fault findings. Trouble shooting techniques and technologies that are not expensive and time-consuming are necessary for rural deployment. Visits to the customer premises make up more than 10 percent of the cost of deploying and maintaining a DSL network. This becomes more expensive in rural areas due to long distances that need to be travelled. Poor roads will mean the frequent and expensive maintenance of cars. Engineering visits to the customer premises have to be avoided as they lead to considerable costs in rural areas. All trouble shooting configurations must take place in the Central Office so as to avoid a need for visiting the customer premises to trouble shoot equipment failures. Solutions that will ensure that fault or failure in a certain area does not affect the whole network will be investigated so as to ensure customer satisfaction and good quality of service.

1.8.4 Future Network Upgrades

Network development is one of the factors that need to be considered when deploying DSL in the developing countries. During the early stages of deployment, it must not be taken for granted that more customers are going to develop interests in the services. This might require network upgrades. That means the DSL network should be designed taking into account the future changes that might be encountered in the spectral compatibilities.

1.9 Research Objectives and Thesis Organisation

The objective of this research is to study the requirements necessary for deploying DSL in the countries dominated by rural areas (developing countries). That includes the quality and design of the existing wire-line infrastructure.

The existing DSL technologies must be studied and investigate the cost effective solutions for the developing countries. That includes pointing out all parameters that affect the deployment costs.

The thesis is divided into 6 Chapters. The first Chapter describes the rural telecommunications scenario, outlining the subscriber patterns and problems that are encountered in xDSL rural deployment. The second Chapter presents an overview of DSL technologies with emphasis on transmission speeds, modulation techniques, power spectral densities, noise, applications and standards. The third Chapter discusses the loop design principles and cost effective techniques that can be used for qualifying the loops for DSL services. Chapter 4 presents the importance of spectral management in DSL network designs. Chapter 5 discusses the solutions on rural DSL deployment with different scenarios. The Chapter achieves this, by investigating several promising DSL solutions in terms of rural expected traffic and costs parameters. The chapter includes a detailed analysis on promising DSL technologies.

Simulations on Chapter 3 and 5 are done using MATLAB and FTW software. In this thesis African regions and South Africa have been used as the reference for developing countries. The thesis is wrapped up by the conclusion and recommended future work on Chapter 6.

Chapter 2
DSL Technologies

2.1 Introduction

The transmission rates and performance of conventional cable and wireless transmission systems depend on the number of subscribers using the network in that particular area. This is because the allocated bandwidth is divided amongst the users in the network at that particular time. This is where DSL takes advantage over these systems. In DSL each subscriber has a fixed bandwidth allocated, which does not depend on the number of subscribers in the network. Each user has a line which is not shared with any other user. DSL solves the problem of conventional dialling up modems, which are known by their time consuming connections. Another contributor to the high speeds of DSL is the fact that DSL bypasses the voice switches in the central office. These switches are often congested by voice calls. Bypassing these switches means conservation of switching resources to the service providers, which means less probability of network congestions. This is because data calls often take longer than voice calls, which these switches were originally designed for.

DSL has a number of technology options, with different transmission speeds, reach and applications. The standardized DSL technologies include Asymmetric DSL (ADSL), very high speed DSL (VDSL), high-bit-rate DSL (HDSL), Symmetric DSL (SDSL), Single-pair High-bit-rate DSL (S-HDSL), and HDSL2 or Rate Adaptive DSL (RADSL) [6]. Some of these technologies have their own different flavours. The word xDSL has been used to define a mixture of these technologies, with *x* representing any DSL technology. This section discusses essential characteristics of these technologies, network components, data rates, reach standards, applications, and modulation techniques.

2.2 DSL Line Codes

DSL services are delivered through the analogue telephone lines. This requires modulation techniques in order to convert the DSL signal to equivalent analogue signals that can be transmitted over the telephone lines. DSL technologies use either passband or baseband codes, depending on the type of DSL technology. Baseband codes can be defined as codes that transmit energy at frequency spectrum translated away from DC. Figure 2.1 shows a typical DSL transmission system. A group of *b* bits from a digital message source is converted into one of data symbols, x_m via *one-to-one* mapping known as an encoder. Each group of *b* bits constitutes a message m, with m = 0,.., M-1 ($M = 2^b$) possible values. The data symbols are N-dimensional vectors, x_m and the set of M vectors form a signal constellation. In the process of modulation each successive data symbol vector is converted into a continuous-time analogue signal $\{x_m(t)\}_m = 0,..,M-1$ that represents the message corresponding to each successive group of *b* bits. The message is then transmitted over the telephone line by taking one of M possible values a time.

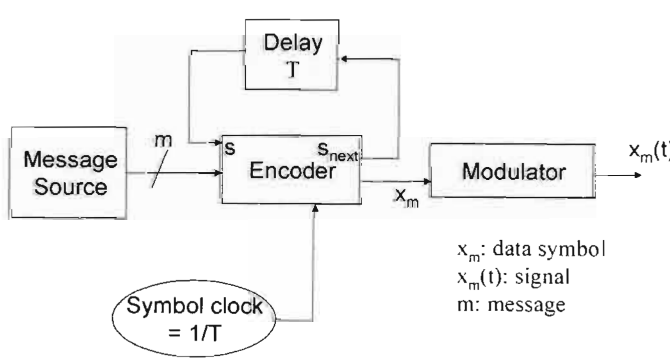

Figure 2.1: Transmitter of a digital system over copper loops

2.2.1 2B1Q

2B1Q is used to abbreviate 2-Binary 1-Quaternary line code. 2B1Q is four level amplitude coding that is used by the earliest DSL technologies, that is ISDN and HDSL [6]. This code has two bits per baud arranged as one quaternary or four level pulse amplitude modulated scheme. This modulation technique transmits data at twice the frequency of the signal. Equation 2.1 shows the basis function that is used by this line code [7].

$$\varphi(t) = \frac{1}{\sqrt{T}} \sin c\left(\frac{t}{T}\right) \qquad (2.1)$$

Where $\varphi(t)$ the basis function / Nyquist pulse, T is the symbol period, and t is the sampling time. The above equation leads to independence of successively transmitted data symbols when sampled at multiples of the symbol period. In the modulation of Figure 2.1, N=1, b=2, M= 4 and the encoder is memoryless. This modulation makes use of the *sinc* function. In reality it is practically impossible to implement and transmit a *sinc* function over a channel with limited bandwidth because of the inter symbol interference (ISI). The standard bodies have developed the pulse masks that will solve this problem. Figure 2.2 (a) shows the constellation diagram for 2B1Q code.

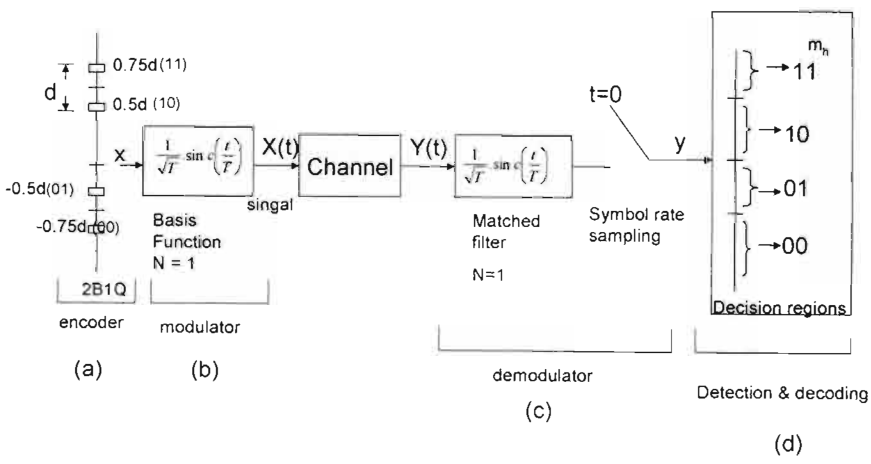

Figure 2.2: 2B1Q Modulation and Demodulation

The number of bits per group is b = 2, and each group of bits maps into one of the four data symbol values as illustrated in Figure 2.2 , where one-dimensional value x could be computed as x = 2m-3, m = 0, 1, 2, 3. The encoding for ISDN and HDSL uses mapping of the bits in Table 2.1. This is done in order to ensure that decoding error to a nearest neighbour results in only one corresponding bit error, hence the unusual bit mapping from input bits to m is often known as gray coding. Equation 2.2 shows the output of a one -sided power spectral density of 2B1Q code [8]. This equation assumes the use of a rectangular basis function with additional gain $\sqrt{T} = \frac{1}{\sqrt{f_0}}$, with also a unity *nth* order Butterworth filter.

$$PSD_{2B1Q}(f) = K_{2B1Q}\frac{2}{f_0}\frac{\left[\sin\left(\pi f/f_0\right)\right]^2}{\left(\pi f/f_0\right)^2}\frac{1}{\left[1+\left(f/f_{3dB}\right)^{2n}\right]} \tag{2.2}$$

where $K_{2B1Q} = \frac{5}{9}V_p^2/R$, and the line impedance $R = 135\ \Omega$. For ISDN, the filter order n = 2, the peak voltage V_p = 2.5 V, $f_0 = f_{3dB} = 80kHz$, the 3dB cut-off frequency, so the data rate is equal to 160 kbps. For HDSL: n = 4, V_p = 2.7 V, $f_0 = 392kHz$, $f_{3dB} = 196kHz$ so the data rate per line is 764 kbps. The probability of error, given an AWGN channel is given by

$$p_e = p_b = 1.5Q\left(\sqrt{\frac{SNR}{5}}\right) \tag{2.3}$$

with an encoder mapping in Table 2.1, where p_b is the probability of blocking and SNR is the signal to noise ratio [56]. It must be noted that Q stands for a Q-function, which is generally given as $Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}}e^{-u^2/2}du = \frac{1}{2}erf\left(x/\sqrt{2}\right)$. The gap for 2B1Q is 9.8 dB at $p_e = 10^{-7}$. ISDN and HDSL also mandate an additional 6dB of margin, leaving ISDN and HDSL at least 16 dB below the best theoretical performance levels. Additional loss of several dB occurs due to ISI on most channels. Thus, 2B1Q is not a high performance line code, but clearly the transmitter is easy to implement.

2.2.2 PAM

PAM has the same function as 2B1Q and simply has $M = 2^b$ equally spaced levels symmetrically placed at about zero, b=1,...., ∞. The number of dimensions remains N=1 and the encoder is memoryless, $x = 2m - (M-1)$, m= 0, ..., M-1 or a code like gray code in 2B1Q and Table 2.1.

Table 2.1 Gray Coding ISDN BR and HDSL Encoder [9]

m	Bit Combination	ISDN (HDSL) Signal Level (Volts)
3	10	2.5 (2.7)
2	11	0.833(0.9)
1	01	-0.833 (-0.9)
0	00	-2.5(-2.7)

Approximately a 6dB increase in transmit power is necessary for the extended constellation points associated by each additional bit in a PAM constellation if the performance has to remain the same. This code is usually used in HDSL or HDSL2 standard as an eight level PAM called 3B1O. The general transmit analogue power across a resistive load R is given by

$$P_x = \frac{\varepsilon_x}{TR} = \frac{M+1}{3(M-1)}\frac{V_p^2}{TR} \qquad (2.4)$$

where ε_x is the average energy of the transmitted signal given by $\varepsilon_x = \frac{1}{M}\sum_{m=0}^{M-1}\|X_m\|^2$, T is the symbol period given by $T = 1/f_0$ and R is the line resistance [56]. The value for R can be anything between 100 and 135Ω. $V_p = (M-1)\frac{d_{\min}}{2}$ is the peak voltage, where $d_{\min}$ is the minimum distance between two constellation points. The power spectral density of the transmitted signal generalises to

$$PSD_{PAM}(f) = K_{PAM}\frac{2}{f_0}\frac{\left[\sin\left(\pi f/f_0\right)\right]^2}{\left(\pi f/f_0\right)}\frac{1}{\left[1+\left(f/f_{3dB}\right)^{2n}\right]} \tag{2.5}$$

with $K_{PAM} = \frac{M+1}{3(M-1)}\frac{V_P^2}{R}$ and f_{3dB} is equal to the cut-off frequency of *nth* order Butterworth transmit filter [57]. The data rate is $\log_2 {(m)}/{T}\, bps$. The probability of error for PAM is given by

$$p_e = p_b = 2\left(1 - {1}/{M}\right)Q\left(\sqrt{\frac{3SNR}{M^2-1}}\right) \tag{2.6}$$

assuming an input bit encoding that leads to only 1bit error for nearest neighbour errors [57].

2.2.3 QAM

Quadrature amplitude modulation (QAM) is an N = two dimensional modulation method. The two basis functions are (for transmission at t= 0)

$$\varphi_1(t) = \sqrt{\frac{2}{T}}\varphi(t)\cos(2\pi f_c t) \tag{2.7}$$

$$\varphi_1(t) = -\sqrt{\frac{2}{T}}\varphi(t)\sin(2\pi f_c t) \tag{2.8}$$

Where $\varphi(t)$ is a baseband modulation function like *sinc* or *square-root raised cosine pulse* shape [58]. QAM pulses suffer from line attenuation in DSLs, and compensation is expensive. For successive transmission, QAM is implemented according to

$$x(t) = \sqrt{\frac{2}{T}}\sum x_{1,k}\varphi(t-KT)\cos(2\pi f_c t) - x_{2,k}\varphi(t-KT)\sin(2\pi f_c t) \tag{2.9}$$

in which one notes the sinusoidal functions are not offset by KT on the *kth* symbol period [58]. QAM basis functions are usually not periodic at the symbol rate, $x_n(t) \neq x_n(t+KT)$, even if the same message is repeatedly transmitted.

2.2.4 CAP

CAP basis functions appear the same within each symbol period. Equation 2.10 and 2.11 show the two CAP basis functions [59].

$$\varphi_1(t) = \sqrt{\frac{2}{T}}\varphi(t)\cos(2\pi f_c t) \tag{2.10}$$

$$\varphi_1(t) = -\sqrt{\frac{2}{T}}\varphi(t)\sin(2\pi f_c t) \tag{2.11}$$

Successive transmissions is implemented with

$$x(t) = \sqrt{2/T}\sum_k x_{1,k}\varphi(t - KT)\cos(2\pi f_c[t - kT] - x_{2,k}\varphi(t - kT)\sin(2\pi f_c[t - kT]) \tag{2.12}$$

where $x_{1,k}$ and $x_{2,k}$ are data symbols. CAP is relatively low in cost and is based on a mature technology. This modulation technique allows DSL modems to take advantage of today's highly sophisticated digital signal processing. CAP dynamically adapts the transmission speeds to the unique loop characteristics of an individual twisted pair to optimize bit rates. CAP is similar to quadrature amplitude phase modulation (QAM), in that the two orthogonal carriers are modulated and then combined. The main difference between the two is that for CAP the orthogonal signal modulation is done using two digital transversal bandpass filters with equal amplitude and $\pi/2$ phase difference. The signals are combined and a digital-to-analogue converter (DAC) converts the combined digital signal back to analogue before transmission. The carrier itself is suppressed before transmission, and hence the adjective carrierless. CAP is different from DMT, for example, CAP offers 7.5 Mbps downstream with only 1 Mbps upstream, while DMT-based ADSL offers 8 Mbps downstream and up to 1 Mbps upstream [10, 20]. DMT technology beats CAP by its unique feature of rate adaptation. CAP divides the signal on telephone lines into three distinct bands, which are Voice Band- 0 to 4 kHz, upstream channel - 25 to 160 KHz and downstream channel - 240 to 1.5MHz. The drawback in carrierless amplitude modulation is the complexity of its receiver.

2.3 DSL Network Architecture and Topologies

Different flavours of DSL consist of a number of different service architectures. All these architectures differ in performance and application. This section considers a few common DSL architectures that are used in today's DSL networks.

2.3.1 End to End DSL Service Topology

Figure 2.3 shows the most used architecture for an end- to-end service.

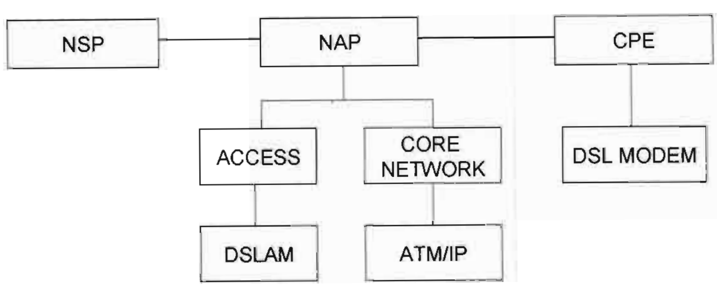

Figure 2.3: End -to-end DSL service topology

This architecture has three main segments, with the first segment being the network service provider (NSP), the second segment is the network access provider (NAP) and the last segment is the customer premise equipment (CPE). All these three segments have their own unique functions.

2.3.2 Network Service Provider

The network service provider is responsible for the type of services that are delivered to the customers. The customer can only receive services that are offered by the service provider. In many countries the network access and the network service provider are different companies with different responsibilities. In case of operators that still have the freedom of monopolising, these two can be done by one company. In case of delivering Internet service, NSP includes both ISP and corporate networks.

2.3.3 Network Access Provider

The network access provider is responsible for the customer premise equipment (CPE), the DSLAM and the core connectivity of the customer to the network service provider. The connection between the customer and the network access provider is normally called the local loop. This is a fibre, twisted pair or coaxial cable. In most cases NAP delivers DSL access to more than one network service provider.

2.3.4 Customer Premise Equipment

Customer premise equipment can be anything installed in the customer premises ranging from the splitter, modem, satellite dish, etc. The type of customer premise equipment depends on the type of service provided to the customer. Some customers may be offered a low speed splitterless ADSL, while others are being offered DSL with the splitter at the premises.

2.3.5 DSLAM

A digital subscriber line access multiplexer may consist of bank of modems with each modem connecting the customer to the central office. In a DSLAM, the data is concentrated from multiple DSL loops onto the core network for connection to the entire network. Because of the improvements in DSL technology, DSLAMS that can tolerate unbearable conditions are now available, with the reason being the rise of architectures that do not place DSLAMS in the central offices. Figure 2.5 shows typical DSLAMS with stinger RT hardened to tolerate the unbearable conditions. DSLAMS are also beginning to interface with other protocols e.g. Paradyne has frame relay integrated into its ADSL access and Pairgain has a special access gateway for its DSLAM which provides encapsulated bridging of Ethernet packets [10] (see Figure 2.4).

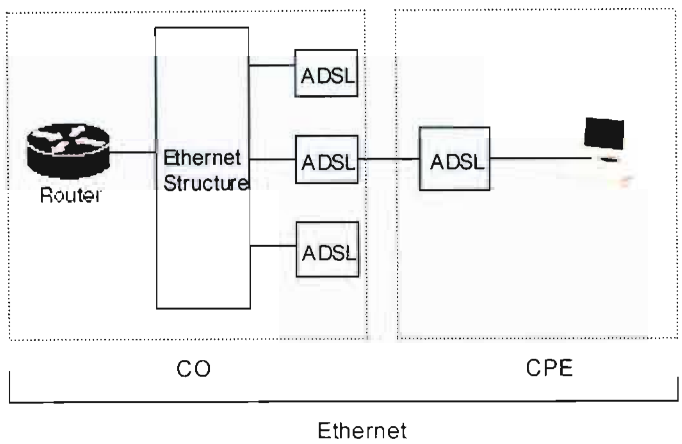

Figure 2.4 Data in the network

In some services DSLAM will also have a responsibility of opening data packets for responding to some protocols. A good example of this is where DSLAM views each packet for supporting dynamic IP address assignment using the Dynamic host control protocol (DHCP). This is done in order to direct packets to the proper destination. This process is referred to as a dynamic host control protocol (DHCP) relay function.

Figure 2.5: Typical DSLAMS [11]

2.3.6 POTS Splitter

Pots splitter is nothing but a filter. POTS splitter is responsible for separating the analogue voice signal from DSL signals. The splitter provides a low pass filter to the basic voice and control telephony signal (below 4 kHz) and a high pass filter for the DSL signals, starting approximately at 25-30 kHz. Most POTS splitter designs are passive, that is without powering requirements. The advantages of passive filters are in their reliability, because they enable continuous telephone service even if the modem fails (for example, due to a power outage). Voice signals are then transmitted to the telephone in the customer premises, and the DSL signal is directed to the DSL modem. Figure 2.6 shows the operation of a POTS splitter for an ADSL application. Since there are DSL technologies that do not require POTS splitter in the customer premise, the installation of a POTS splitter remains optional.

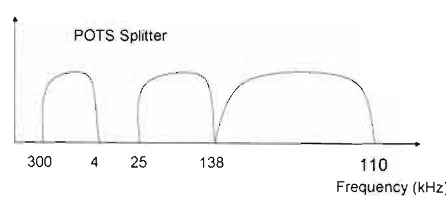

Figure 2.6 : POTS splitter on ADSL

2.3.7 Centralised Architecture

Aggregation of subscribers occurs in a centralised location where it can terminate a number of subscribers. This architecture requires that subscribers from various central offices of the service provider get aggregated in various centralised point of services before the subscriber traffic is handed over to the Network Service Provider. Figure 2.7 shows a typical centralised xDSL architecture.

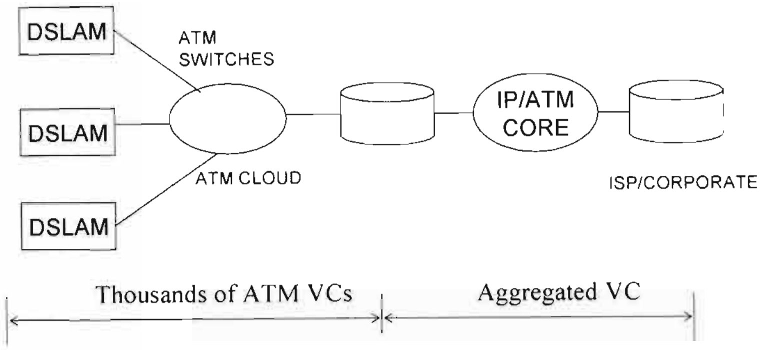

Figure 2.7 : Centralised architecture

In this architecture DSLAM acts as a multiplexer for a number of subscriber modems and switch the subscriber data over a common trunk.

2.3.8 Distributed Architecture

The introduction of IP switch in the DSL networks has driven the service providers to investigate a number of possible architectures and challenges that can be addressed. The IP DSL switch is an outcome of combining the DSLAM and aggregation functionality into the same device. Figure 2.8 shows a typical distributed architecture.

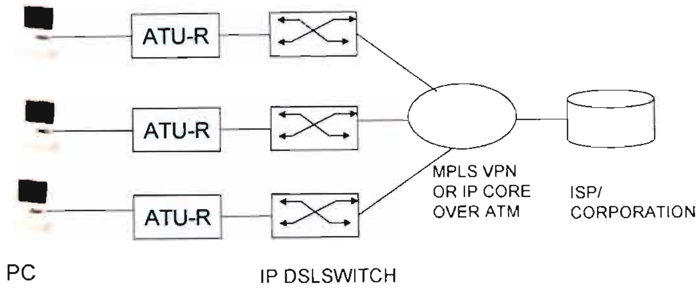

Figure 2.8: Distributed Architecture

In this architecture the IP switch functions as an aggregation device, aggregating the subscriber virtual connections (VCs) using common access encapsulation methods. The IP DSL switch can also act as a provider edge device for MPLS cores and can offer virtual private network (VPN) services. An IP DSLAM acting as premise equipment (PE) router can associate the incoming subscriber traffic to their corresponding VPNs. A PE usually sits at the edge of the service provider's (SP's) network and communicates with various customer equipment (CE) routers in customer's networks. Performing these functions not only results in fewer PVCs in the access core of the SP network, but also reduces the number of additional elements required in the network. It also saves capital expenditures for the SP. SP also benefits a flexibility of being able to migrate their ATM based core infrastructure to IP, adding IP to their existing ATM infrastructure to make it more scalable and moving from centralised to distributed architecture. Distributed architecture can be taken as the best, compared to centralised architecture. Service providers no longer experience the delays associated with PVCs provisioning, because the subscriber can be provisioned on the same network object, the IP switch.

2.3.9 Centralised Vs Distributed Architecture

Table 2.2 shows the advantages and disadvantages of centralised against distributed architecture.

Table 2.2: Centralised versus distributed architecture

CENTRALISED ARCHITECTURE	DISTRIBUTED ARCHITECTURE
Aggregation device terminates subscriber traffic from different DSLAMs serving different regions.	Aggregate subscribers at DSLAMs, not as separate aggregation device
Aggregation device supports and terminates a number of subscribers	IP DSL switches terminates only a few number of subscribers
Easy to implement and manage subscribers for a particular ISP	Not easy to implement and its difficult to manage subscriber traffic delivered to ISP from IP DSL switch distributed across different regions
A network failure affects all subscribers	Only those few subscribers that are served by faulty IP DSL switch will be affected.

Today's networks are migrating to a range of new architectures, rather than just a point -to-point network, with IP being the unified network layer for new network services such as voice over IP (VoIP) o Video on demand (VOID).

2.4 DSL Standards Review

In order to ensure the interoperability in the xDSL technologies, DSL technologies have been standardised. The current active DSL standard bodies include International Telecommunications Standards (ITU); American Standards Institute (ANSI) and Engineering Telecommunications Standard Institute (ETSI). Table 2.3 provides a summary of ADSL technology standards from 1999 to the latest version of 2003 [12, 6]. These data rates can change depending on the parameters discussed in the next chapters.

Table 2.3: DSL standards

Family	Description	Upstream Rate	Down Stream	Ratified
ADSL	G.992.1 G.dmt	1Mbits/s	8-10Mbits/s	1999
ADSL	G.992.2 G.lite	512kbits/s	1.5Mbits/s	1999
ADSL2	G.992.3 G.dmt.bis	800kbits/s	8Mbits/s	2002
ADSL2	G.992.4 G.lite.bis	800kbits/s	8-12Mbits/s	2002
ADSL2	G.992.5ADSL2 +	800kbits/s	16Mbps	2003

2.4.1 ADSL (Asymmetric Digital Subscriber Line)

ADSL is the most popular digital subscriber line technology in the market. ADSL dominates the worldwide deployed DSL technologies. Figure 2.9 shows ADSL world market penetration [13].

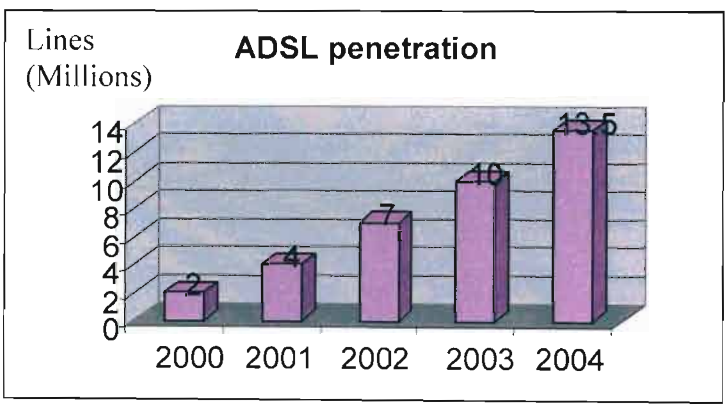

Figure 2.9: ADSL market penetration

One of the reasons for high ADSL penetration is that ADSL fits most of the broadband applications. This technology is suitable from residential to high bandwidth business subscribers. Table 2.4 shows ADSL applications with equivalent required bandwidth for both business and consumer subscribers. ADSL is expected to continue dominating the DSL market, especially the residential market. This is because most of the residents receive information downloads. The residential market is high volume and low margin which makes it more suitable for ADSL [14].

Table 2.4: ADSL applications with equivalent required bandwidth

Consumer Application	**Required Bandwidth (Mb/s)**
Shopping	0.500-1.5
Internet	0.500-1.5
Education	0.500-6.0
Interactive video games	0.128-6
Video on Demand	3.0-6.0
Business Applications	
Telecommuting	0.014-6
Internet	0.5-1.5
Distance learning	0.5-6
Local website hosting	0.5-6
Telemedicine	0.5-6
Computer Telephony Integration	0.128-1.5
Desktop video conferencing	0.128-1.5

ADSL also gained its popularity on bringing broadband services to homes.

ADSL is capable of supporting the highest video quality. Unlike other DSL technologies, ADSL allows the use of the telephone line for DSL signals and voice simultaneously. That means less investments required from the provider as it needs no other expensive copper cabling. ADSL transmits at higher speeds from the central office to the subscriber. The bandwidth allocated for transmitting towards this direction is often referred to as the down stream bandwidth. The maximum down stream bandwidth is 8Mbps. Towards the central office is an upstream bandwidth with a maximum of 1Mbps. This asymmetric ADSL makes it ideal for a user who needs more down stream bandwidth than upstream bandwidth. If the average customer uses the Internet for browsing through web pages, downloading documents, and playing movies, this user requires a much higher downstream band than an upstream band. The user will be using upstream band to request information, and then downstream to receive all of the information that was requested. Often the requested information will be much greater in size than the sent information. Like all DSL technologies, the reach on ADSL depends on a number of factors. These factors are mostly related to the quality of the already deployed loop plant. This will be discussed in detail on Chapter 3. The current DSL reach range is 5.5km from the central office. The ADSL standards are also defined by ETSI and ANSI.

2.4.1.1 ADSL Vs Ordinary Modem

Asymmetric feature on ADSL makes it different from an ordinary modem. An ordinary modem transmits at symmetrical speeds of 64 Kb/s. That means the transmission speeds of ADSL are 20 times the transmission speeds of ordinary modem. ADSL is directly connected to the internet, which means there is no need for a time consuming dialling up connection like in ordinary modem. It is not possible with ordinary modem to use both the internet and telephone simultaneously.

2.4.1.2 ADSL vs. ISDN

Before the foundation of ADSL, ISDN was the fastest wire-line transmitting technology. ISDN is known to be transmitting at 128Kbps in both directions [15]. When ADSL was found ISDN speeds were no longer appreciated. ADSL speeds are a number of times faster than the transmission speeds of ISDN. One of the reasons is that ADSL bypasses the telephone switches which are already overloaded by telephone calls. ISDN also does not allow the simultaneous use of telephone and Internet.

2.4.1.3 ADSL Vs Cable Modem

Cable modem service providers claim to have transmission rates of about 35Mbps. This is not true because for a cable modem, the available total bandwidth is divided amongst the users that are subscribing at that particular time. That means for a cable modem there is no fixed allocated bandwidth for a particular customer. Cable modem, like ADSL, needs no dialling up connection and also allows the simultaneous use of internet and telephone. Crosstalk at high transmission rates also becomes a threat in high user environment.

2.4.2 Rate Adaptive Digital Subscriber Line (RADSL)

Rate adaptive digital subscriber line (RADSL) is another version of DSL, designed to tolerate the loop plant impairments. The transmission speeds of this technology are not fixed. RADSL decreases the deployment costs as it does not necessarily require the advanced and expensive sophisticated loop qualifying techniques. This technology monitors the loop conditions at all times and adjusts the transmission speeds according to the loop conditions. Loop conditions can change at any time e.g. if rain water manages to get into the copper bundles. When the loop conditions become terrible, other technologies like T1/E1 and BRI-ISDN do not work at all. This technology is ideal for areas with loops that are not of a good quality, like rural areas. RADSL relies basically on sacrificing the data rate. This technology is good only for consumer applications. A subscriber is not guaranteed a specific bandwidth.

2.4.3 ADSL (GDMT) - (ITU-T G.992.1)

This is the first and the well known standard ADSL technology. GDMT allows the downstream transmission rates of 8 -10 Mbit/s and the upstream transmission rates of 1Mbit/s. over a range of 3km [12]. This is a high bandwidth technology as it allows all the applications indicated on Table 2.4. This is a suitable technology for applications that require extreme high bandwidth.

2.4.4 ADSL (GLITE) – (ITU-G.992.2)

ADSL vendors and carriers recognized that a reduction of speed could simplify the modem design. Reducing hardware complexity was the solution to vendors with interests of deploying DSL at a large scale. GLITE which is draft version of ITU-T recommendation specifying splitter-less ADSL appeared in October 1998. GLITE is one of the flavours of ADSL.

This specification was approved by ITU-T in 1999 as a recommendation G.992.2. GLITE came up as a solution on long periods of DSL deployments [16]. These long DSL deployments were accompanied by high costs. The very useful advantage of this technology is that it does not require the installation of the splitter circuit at the customer premises as it is in the RADSL and the standard ADSL. This means there is no need for sending a technician to the customer premises. This is a significant saving especially in the rural environment. Customer visits to rural areas are expensive as they always go with the servicing of cars that travel long distances on poor roads. Splitterless DSL are just plug-and-play devices. The configurations can even be set by the customer. All necessary troubleshooting can be done in the central office. This technology has also taken an advantage of the trade-off between the reach and bandwidth. The reach has been increased here to 5.4km, with low transmission rates of 1.5Mbit/s downstream and 512 kbit/s. Looking from Table 2.4 it can be seen that with this technology, a number of both business and consumer applications are possible. This includes Internet, desktop video conferencing, computer telephony integration, and online shopping. GLITE standard technology is also rate adaptive. When-ever GLITE modem senses impairment on the loop, it decreases the power. The data rates will also be low because of the low power in the modem. This technique is referred to as the fast retrain. The splitter less ADSL system uses 128 frequency channels for the downstream data. In such scenario, the ADSL modem and the POTS operate together on the same home wiring system. This explains the reason for the splitter at the customer premises being optional

2.4.5 ADSL2/ADSL2+ (ITU-T G.992.3/G.992.4)

The new ADSL standard is characterized by better performance on long lines. This feature is in great demand in rural environment. Transmission over long lines is characterized by low SNR at the receiver end. ADSL2 combats this by its better modulation efficiency, which provides higher data rates where SNR is low. Higher coding gain on long lines with low data rates is achieved. Figure 2.10 shows a 50kbs data rate increase on long lines [6]. This results to a coverage increase of 6% [12], which is one of the service provider goals.

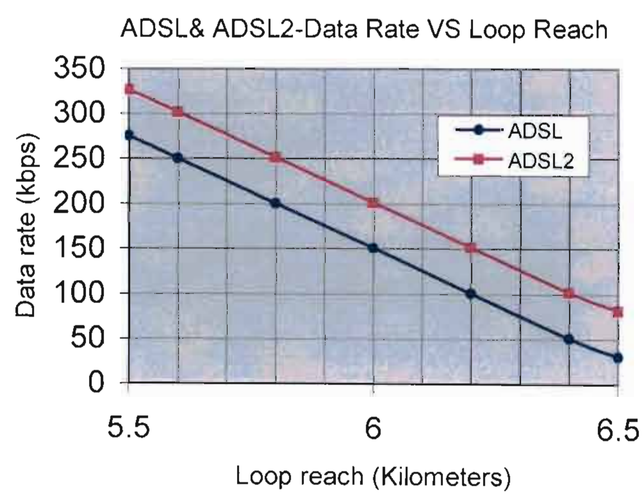

Figure 2.10: ADSL and ADSL2+

2.4.5.1 Fault Findings

ADSL2 comes with a package of tools for troubleshooting during and after installation. This monitors the performance and checks if there is a need for an upgrade to high data rate services for a particular customer. This is done by remote measuring of line noise, loop attenuation and SNR at both ends of the line by transceivers.

2.4.5.2 Power Savings

ADSL2 can operate in full power mode when large files are downloaded and in low power mode when the traffic decreases. When there is no traffic it switches to a sleep mode. Some rural areas in South Africa still suffer from the unavailability of electricity. This low power consumption feature can allow the use of solar energy.

2.4.5.3 Rate Adaptation

This solves the problem of crosstalks and any other source of noise. It is done by detecting changes in the channel conditions and changes the data rate to the new channel condition.

2.4.5.4 Increasing the Data Rate

Data rates can be increased by bonding multiple phone lines together. Figure 2.11 shows the increase in data rate due to bonding.

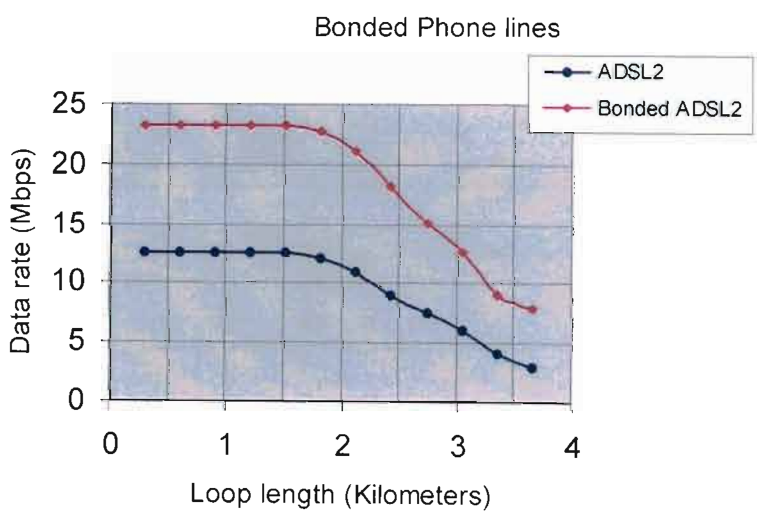

Figure 2.11: Bonded Phone lines

2.4.5.5 ADSL2+ Transmission Frequency

The ADSL2+ supports the downstream frequency bands of 1.1MHz and 552 KHz and ADSL2+ supports a downstream band of 2.2 MHz on shorter phone lines. From the central office to the remote terminal ADSL2+ uses 1.1 MHz and between 1.1 and 2.2 MHz from remote terminal to customer premise which results in reduced crosstalk [6].

2.4.5.6 The ADSL Transmission Frequencies

The existing loop plant was originally designed for voice communication. The voice operating frequencies are below 4Hz. Since the plain old telephone services (POTS) does not make use of frequencies above 4 kHz, this means there is a challenge with transmitting the DSL signals. Any modifications that can be done in the POTS must not disturb the operation of the original existing services, which the POTS were designed for. This lead to a need for a spectral arrangement of the services that will be provided using the same loop plant. A transmission bandwidth of ADSL is 1.1MHz downstream and 256 kHz upstream for transmission data rates of 6Mbps downstream and 640Kbps upstream [32]. The frequency domain is divided into 256 sub-channels of 4 KHz, with the 0-4KHz channel being allocated for original service, which is voice and 2-6 channels are left unused. This is done in order to combat interference of the new deployed DSL services with current voice communication technology. This also makes it easier to design splitters to filter out voice frequencies from data transmitting frequencies. Frequency Division multiplexed (FDM) is one of the two well known ADSL modulation techniques. FDM has upstream and downstream channels that uses different frequency ranges. Upstream uses 7-32 and downstream uses 32-256. The second modulation technique is Echo Cancelled (EC) with overlapping upstream and downstream channels. An upstream uses 7-32 channel while downstream uses 7-256 channels. The transmitted and the received signals are independent of each other.

2.4.6 Modulation in ADSL

2.4.6.1 Multi Carrier Modulation

As the name implies, multicarrier modulation divides a channel into numerous Quadrature Amplitude Modulation (QAM) modulated sub channels and transmits data on each one. Figure 2.12 shows the QAM modulation.

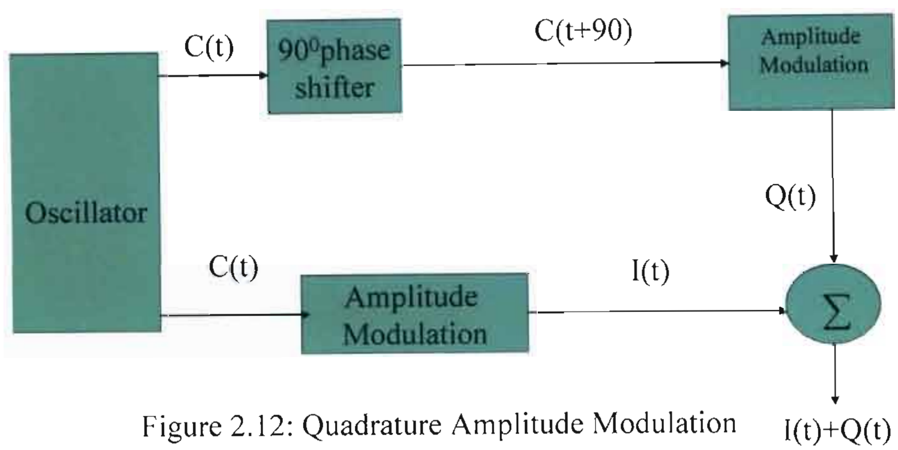

Figure 2.12: Quadrature Amplitude Modulation

The technique has a considerable theoretical support as on optimum code, but has been troubled by the cost. Multiple channels are being realized with digital techniques using a fast Fourier transform, giving rise to Discrete Multi Tone (DMT), the version of multicarrier used in ADSL. DMT's ANSI T1.413 standard specifies 256 subcarriers, each with a 4 kHz bandwidth [17]. They can be independently modulated from zero to a maximum of 15b/s/Hz. This allows up to 60kb/s per tone. At low frequencies where copper attenuation is low and the signal to noise ratio (SNR) is high, it is common to use very dense constellation. In unfavorable line conditions, modulation can be relaxed to accommodate a lower SNR, usually 4b/s/Hz or less, and still deliver the necessary noise immunity. There is also a third variant called discrete wavelet multitone (DWMT), in which the wavelet transform is used to achieve multi-channel modulation instead of fast

Fourier transform (FFT). It is claimed that this will improve the system performance by improving the spectral containment of the channels. DMT is an ANSI chosen standard for ADSL line code system. DMT divides the signals into separate channels, and divides the data into 247 separate channels each 4 kHz wide. The data transmissions channels are partitioned into a set of parallel sub-channels, each with its own carrier, while the carriers form an orthogonal set. Data transmission in one sub-channel is independent of the data transmitted in other sub-channels and channel is partitioned such that each sub-channel has a near flat response. Therefore DMT modulation becomes the most preferable because of its computational ease.

There are, however, many problems that arise in trying to send so much information at fast speeds. DMT are transmitted over lines in frequency bands known as bins. Each bin is uniformly spaced every 4.3125 kHz. There is 4 kHz of usable bandwidth in every bin with the additional 312.5Hz being used as a band to prevent inter-bin interference. Each of the bins contains data from the user to central office (CO). As mentioned before, the standard ADSL system uses 32-256 channels downstream and 7-32 channels upstream. Modulation of DMT can be carried out by Inverse Fast Fourier Transform (IFFT) while the demodulation can be carried out by Fast Fourier Transform (FFT). Implementation of N sub channels of DMT requires 2N size FFT. Real-valued time domain samples will result to forced conjugate symmetry in the frequency domain. Figure 2.13 shows the general structure of a DMT system, where $\{X_0, X_1, \ldots\ldots\ldots\ldots, X_{n-1}\}$ are the original complex, input data symbols, $\{X_k\}$ is the modulated data sequence, $\{Y_k\}$ is the received sequence and $\{Y_0, Y_1, \ldots\ldots\ldots\ldots, Y_{n-1}\}$ are the decoded complex data symbols. $\{P_i\}$ and P_i^* are the modulating and demodulating othonormal vectors. DMT allows the efficient utilization of bandwidth by varying the data rate based on Signal to Noise Ration (SNR) of individual sub-channels.

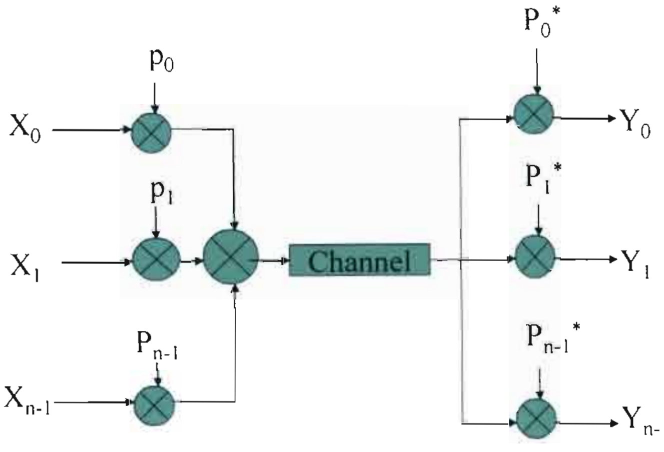

Figure 2.13: Basic DMT modulation scheme

In terms of complexities, DMT remains more complex than, CAP.

2.4.6.2 DMT Challenges

There are many challenges that arise when trying to transmit DMT over ordinary telephone lines. One particular challenge is transmitting DMT over long distances. The distance depends on the data rate and wire gauge. Table 2.5 below shows how data rate and wire gauge affect the distance and Table 2.6 shows the relationship between attenuation and the transmission distance of a 24 wire gauge wire signal at a frequency of 1.1MHz [19].

Table 2.5: The effect of wire gauge on reach and bandwidth

Data Rate (Mbps)	Wire Gauge (AWG)	Wire Size (mm)	Distance (Km)
1.5-2	24	0.5	5.5
6.1	24	0.5	3.7
1.5-2	26	0.4	4.6
6.1	26	0.4	2.7

Table 2.6: Trade off between distance and attenuation

Length of line (Km)	Attenuation (dBm/Hz)
3.05	-70
3.66	-90
4.27	-100
4.88	-110
4.49	-120

It can be seen in the Table 2.5 that, the distance that DMT can be transmitted decreases with the increase in data rate. Table 2.6 also shows that attenuation increases with the increase in distance. In order to transmit longer distances, some measures need to be taken. One of them is to introduce amplifiers in the subscriber loops. However, designing the amplifier is not an easy task because if there is a slight phase shift, the decoding of the information in the signal will result in incorrect output. QAM signal is a unique signal that occurs within the band. DMT is also the official ITU-T standard for ADSL. Other ADSL system requirements include qualifying the loop for the efficient transmission of DSL signals. This is going to be discussed in more detail in the third chapter.

2.4.7 ADSL System Architecture

A typical ADSL system architecture is illustrated in Figure 2.14.

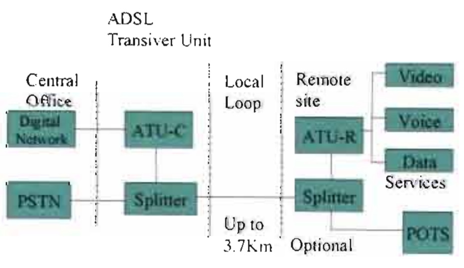

Figure 2.14: ADSL system architecture

At the central office there is an ADSL terminal unit and optional splitter circuit. The ATU-C interfaces with the network switching, transport, and is also responsible for multiplexing and network operations. Depending on the architecture it may be located in a central office or in a remote location. The ATU-C functions are usually integrated within a higher-level network element, e.g. DSL access multiplexer (DSLAM). DSLAM contains the access interface (network termination – NT) to the appropriate transit network, e.g., ATM, Frame Relay, etc. At the customer end is an ADSL Terminal Unit-Remote end type (ATU-R) together with a splitter circuit. ATU-R may present the interfaces to the local distribution for broadband services via service modules (SM) and set-top boxes. The SM contains necessary decoders and terminal interfaces for the given service and customer control interfaces. With the use of Splitters the telephony signals and the ADSL signal can be transmitted over the same copper loop without interfering with one another.

2.4.8 VDSL (Very High Bit-Rate Digital Subscriber Line)

Many technologies have been deployed to deliver broadband services to the people.
Most of these technologies are considered expensive as they need new core network investments. VDSL comes as one of the technologies exploiting the high possible bandwidth that can be transmitted over copper line. VDSL technology resembles ADSL to a large degree, with reason being that VDSL evolved from ADSL technology. VDSL is the latest wire-line broadband access technology. The main difference between ADSL and VDSL is that ADSL can transmit over longer distances with rates lower than that of VDSL. Another difference is that ADSL can transmit only at asymmetrical rates, but VDSL can transmit both symmetrical and asymmetrical rates. This feature gives VDSL an increased flexibility in meeting a number of applications. The reuse of copper in large buildings, business areas, educational institutions etc, enables VDSL to serve growing bandwidth demands cost effectively.

2.4.8.1 VDSL Drivers

In countries with high VDSL penetration rate, the main focus has been on providing residential access, with the second goal being to deliver broadband services to the business sectors. Today's residents demand higher bandwidth applications than before. VDSL has got many features that make it an economical and full service broadband technology. This technology supports high bit transmission rates, low cost multiple megabit data services, efficient use of plain old telephone services (POTS) infrastructure and compatibility with Ethernet services. VDSL competes with other access technologies like Fibre to the home (FTTH) and wireless last mile broadband technologies. Most of the telecommunications companies deployed VDSL for the purpose of substituting expensive fibre to the building technology. Most of the broadband service providers have been deploying VDSL using a fibre to the cabinet technology. As compression technologies progress over time the *limited* bandwidth of VDSL will not necessarily be a significant limitation versus fibre for many applications. With this architecture, the existing copper is used instead of construction of a full FTTH network. This technique best satisfies the need for higher bandwidth services while minimizing expensive plant upgrades. VDSL architecture has got an advantage of security benefit, provided by point to point links. This is a significant advantage over technologies which rely upon bus architecture, e.g. HFC networks.

2.4.8.2 VDSL Line Codes

VDSL uses Quadrature amplitude modulation (QAM) and discrete multitone modulation DMT).

2.4.8.3 DMT as a VDSL Transmission Line Code

VDSL inherited DMT line code from ADSL. Although that is the case, implementing this line code for VDSL is more complex than implementing it on ADSL. Implementing this modulation technique requires a lot of intensive digital signal processing which makes it expensive. Another disadvantage of DMT is that, it is a high power consuming technology. DMT works by creating a series of individual symbol sequencing from the data stream and modulates each symbol sequence by a distinct carrier tone. A complex technique based on the characteristics viewed by the receiver is used to assign bits to each carrier. The receiver reverses the modulation of each carrier and performs a frequency to time domain transformation in order to reconstruct the data sequence. DMT requires time for frequency and serial to parallel stream conversion before any counter measures against analogue noise can be taken. Conversion for analogue to digital and vice versa; and line drivers consume a lot of power. DMT requires 2 bits more than QAM for resolution, in order to cope with high signal swings. This alone doubles the power consumption of the line driver.

2.4.8.4 QAM as A VDSL Transmission Line Code

QAM seems to be the most suitable current line code for VDSL. Implementing this code is not expensive and it is a low power consuming technology. QAM focuses on time domain processing of the VDSL signal, thus taking into account the serial and analogue nature of the signal on wire, and jointly optimising digital and analogue components of the system. A sequence of the symbol is modulated from the data source to a desired transmission frequency. The receiver detects the signal and corrects the distortion caused by the attenuation of the twisted pair line. Decision feedback equalization and forward error correction techniques are used to overcome the impairments.

2.4.9 VDSL Applications

VDSL was designed to be a full broadband service. That means it was designed to support voice, data and video at the same time. Since VDSL enables much higher bandwidths than established mass market DSL technologies like ISDN and ADSL, it is usually associated with the delivery of a number of services. VDSL provides the high speed internet access as well as voice services. Due to increased bandwidth availability VDSL can provide services such as file down/uploading, video on demand, high definition television, Broadcast TV, tele-medicine, teleconferencing, digitally encoded video etc. These video services typically consist of multiple channels of MPEG encoded data, today requiring from 6 to 8 Mbps for sequences with fast movements and good picture quality. Several business applications are also possible and promise additional evolutionary growth where copper can provide high speed pipes for access in a campus or high rise building environment. This is because VDSL is able to transmit even up to 26 Mb/s in both directions [18]. At least two simultaneous video streams must be delivered in order to compete with the near video on demand systems currently offered by cable TV Operators. These services drive the bandwidth requirements for asymmetric VDSL to deliver at least 13 Mbps downstream and 1 Mbps upstream. One significant symmetrical application is the extension of corporate Ethernets which drives the requirement for symmetrical bandwidth of at least 10 Mbps. VDSL can be thought of as a technology promising to deliver full service network. It is reasonable to estimate that future applications in the developing countries will demand high-bandwidth capabilities like those offered by VDSL.

2.4.10 VDSL Standardisation

There are currently three organizations developing VDSL transceiver standards; ITU-T, ETSI and ANSI (FSAN acts through contributions to these organizations).There are agreements between all of them to promote cooperation and to work towards the final standards with as few differences as possible. There are some important differences in the goals between the different bodies, which results in differences between them in focus and output.

2.4.11 Relationship between VDSL and ADSL

ADSL was invented to offer Video on demand (VoD) over copper pair. Using MPEG-2 compression, each video stream takes about 3Mbps to achieve 30 frames per second, a standard rate at which broadcast television operates. To reach a high percentage of households with the existing copper distribution network at high bandwidth, VDSL system utilises only one twisted pair and coexist with POTS and ISDN. VDSL has an advantage of compatibility with Ethernet. VDSL incorporates high bit-rate capabilities and low-cost multiple megabit data services. To handle numerous high-bandwidth applications, VDSL can support speeds up to 52 Mbps. The high frequency band used (up to 20 MHz) raises many to the already installed DSL technologies. Some of these challenges include spectral compatibility, RF interference sources, and transmissions in far end crosstalk (FEXT) noise. Table 2.7 shows the bandwidth that can be delivered with asymmetrical VDSL at a particular distance [19].

Table 2.7: VDSL reach and equivalent bandwidth

Typical range (m)	Bit rate (Mbps) down	Bit rate (Mbps) up
304.8	25.92-51.84	3.24-6.48
914.4	12.96-25.92	1.62-3.24
1,371.6	6.48-12.96	1.62-3.24

2.4.12 VDSL Advantages

VDSL incorporates high bit-rate capabilities, low-cost multiple megabit data services, use of Plain Old Telephone Service (POTS) infrastructure and compatibility with Ethernet. High bit-rate permits VDSL to handle numerous high-bandwidth applications. Low-cost, multiple megabit data services are provided by the high-compression capabilities of VDSL and the efficient use of POTS infrastructure. VDSL can be implemented symmetrically, which is ideal for services like video on demand and for businesses that require high bandwidth for both up and downstream transmission. VDSL is available in asymmetric forms, which makes it even suited for residential applications. Residences can receive combined television, Internet access and video services along with lifeline POTS. VDSL is the only type of DSL that is capable of supporting true Ethernet extensions. This is an important feature of VDSL because it allows connectivity using

Ethernet standards. The widespread use of Ethernet is another factor that assists in reducing implementation costs.

2.4.13 HDSL

High-bit-rate Digital Subscriber Line (HDSL) derives its name from the high bandwidth that is transmitted in both directions over two copper loops. It is the earliest version of DSL. HDSL has proven to be a reliable and cost effective means for providing repeater-less T1 and E1 services over two twisted pair loops. T1 is a 1.544 Mb/s digital transmission link and is mostly used in North America while E1 system transmits at 2.048 Mb/s. HDSL transceivers can reliably transmit a 2.048 Mbps data signal over two non-loaded, 24 gauge (0.5mm), unconditioned twisted wire pair loops at a distance of up to 4.2 km without the need for repeaters [20]. Eliminating the need for repeater equipment and removal of bridged taps significantly simplifies the labour and engineering effort to provision the service. This attribute eliminates the need to identify, modify, and verify a controlled environment with power, secured access, and other factors needed to support repeater equipment. It also reduces the time, cost, and effort of isolating faults and taking corrective action when a failure does occur.

Studies by some service providers have indicated that trouble shooting and replacing defective repeater equipment often costs significantly more than the cost of the equipment itself. Faster service provisioning leads to increased customer satisfaction and increased service revenues

2.4.13.1 Modulation in HDSL

Baseband and Passband Transmission Schemes

Two modulation schemes were competing for HDSL, 2B1Q line code, which is four-level baseband pulse amplitude modulation (PAM), and passband quadrature modulation (QAM). The line code 2B1Q successfully used in ISDN basic access also reached a good performance in HDSL environment. The combination of performance and relatively low complexity were essential for its acceptance. On the other side, QAM has the best combination of bandwidth, performance in the presence of noise and timing robustness. Trellis coded modulation may be also applied to either PAM or QAM to achieve coding in system performance. The performance of QAM and PAM schemes with fractionally spaced equalization on long loops at the extreme range of a CSA are similar. Trellis coded modulation received with parallel decision feedback equalizer shows slightly higher coding gains when applied to QAM than it does when applied to 2B1Q. It was also shown that QAM has better tolerance to impulse noise than 2B1Q. If compared with the QAM, the advantage of CAP reflects in some digital implementation efficiencies.

2.4.14 SHDSL/SDSL

The single pair digital subscriber line of a data rate of 1.544 Mb/s was developed in early 90's. This technology had a maximum reach of less than 3.6576 Km over a 26 AWG twisted pair [21]. This was a drawback on providing the remote subscribers with this technology. As the technology is evolving, later it was proved that single duplex transmission of 1.544 Mbps is possible on loops designed with carrier service area (CSA) specifications. Single-pair High-bit-rate DSL (S-HDSL/SDSL) operates on a single copper pair as opposed to the traditional two-pair HDSL described above. S-HDSL/SDSL allows easy implementation of applications that require symmetric data rates on a single local loop while maintaining the existing POTS on the same loop. Because only one pair is needed in this arrangement, the capacity of the entire local loop infrastructure is greatly magnified. With this capability, local providers can extract the maximum value from their existing plant, or deploy new capacities both more quickly and at a lower capital expenditure. This allows for rapid and cost effective deployment of intermediate data rate services. Potential uses for this technology include Work-at-home LAN Access, Distance Learning, Internet Access, and Campus or Large Facility LAN to LAN connectivity.

2.4.15 HDSL2

HDSL2 is the next generation of HDSL. This technology got its recognition when it was standardized in 1995 [6]. This technology is an improvement of the original HDSL. The transmission rates and the reach of this technology is the same as the first HDSL technology. The spectral compatibility also remains the same as the traditional HDSL. Standardisation of this technology solved the problem of vendor interoperability, which means the service providers are no longer tied to proprietary solutions. In order to be an interoperable product, among many criterion defined by the HDSL2 standard, all products must use the HDSL2 OPTIS line code, which was invented by Pair Gain Technologies. Pair Gain is known as one of the contributors in the development of the DSL standards trough ANSI. PairGain's proposal will mean that only Vendors that adhere to the standard by using OPTIS will all be interoperable. Unfortunately there are currently some vendors claiming to have HDSL2, but they are not using OPTIS. HDSL2 can also extend to full CSA reach which is 3.6576 Km.

The major difference between these two technologies is on copper savings, as HDSL2 requires only one copper pair instead of two like in the original HDSL. This becomes a major advantage for areas that have been provided with limited copper pairs. In areas with more than one copper pairs, service providers have got an advantage of switching between pairs if there is a problem with any of the pairs. This feature can also be archived with SDSL, but HDSL2 remained advantageous because SDSL was not standardized while HDSL2 was already standardizes. HDSL2 uses more advanced modulation techniques. Crosstalk is controlled by carefully selected offset frequency placement of the up and downstream directions. The new version of this technology has inherited a lot of good features from ADSL. The rate adaptive high bit rate digital subscriber line (RHDSL) is on the way. This will mean the combination of the strengths of ADSL and the strengths of HDSL.

2.4.16 IDSL

ISDN was the original digital subscriber line. IDSL is the ISDN DSL. The transmission speed for IDSL is the same as that of ISDN, which is 128kb/s [22]. The difference between the two is that IDSL does not terminate on the ISDN switch like ISDN, instead it's terminate on the router and passes traffic typically to the Internet. That means a subscriber connected to IDSL has a dedicated access, not a switched service. Since IDSL terminates at the router rather than a digital switch, it means that it can not support voice traffic as ISDN does. Like ISDN, IDSL requires a single pair and can be deployed to subscribers located at a distance of 5.5 km from the central office. The main disadvantage of ISDN is that it makes no provision of 4 kHz analogue voice channel and has got a limited bandwidth.

2.5 Conclusion

In general, the provision of high quality multimedia services requires an upgrade of the existing network infrastructure in the access network, as the access network is the most expensive part of communications networks. DSL technology relies on the reuse of the existing wire-line network. All the DSL technologies have their own unique characteristics and applications. This shows the selection of an appropriate technology for being deployed at a particular region is necessary. Some technologies might not work in other areas because of some certain limitations. This will be explained in more detail in Chapter 3. These technologies can be costly if they are not deployed to relevant customers and loops.

Chapter 3

Loop Design Principles and Qualification

3.1 Transmission Characteristics of Twisted Pair Cables

A twisted copper pair is a cable twisted at uniform intervals of 50 to 150 mm. It is this cable that connects the subscriber to the central office. This physical connection is referred to as a local loop. These cables are usually insulated with polyethylene. The common diameters for these cables are 0.4mm, 0.6mm, 0.5mm and 0.9mm. These cables diameters are usually given in American Wire Gauge (AWG) as seen in Table 3.1. In this thesis these cable sizes will always be given in AWG.

Table 3.1: Wire gauges and diameters [22]

AWG wire size	Diameter (mm)	Resistance per km (ohms)
24	0.51	87.5
22	0.64	51.7
20	0.81	34.1
18	1.02	21.9
16	1.29	13.0
14	1.63	8.54
12	2.05	5.4
10	2.59	3.4

Figure 3.1 shows a stranded bulk cable with 4 twisted pairs.

Figure 3.1: Stranded Bulk Cable / 4 Pairs

These cables have a large across section near the central office. At this point the cables are bundled in groups. Each cable binder group can have 10 to 50 pairs and up to 50 binder groups per cable. Bundling these cables introduces some complications in DSL transmissions. That will be discussed in crosstalk analysis. As you move along the loop from the central office towards the customer premises, the number of pairs drops, until a two or four pair wire (depending on a particular country) is dropped in the customer premises. The drop wire can either be hung on poles or buried.

3.1.1 Single Pair Transmission Characteristics

Consider a single pair with a uniform insulation and a distance of *2a* between the centres of each conductor, with the radius of each conductor equal to *r* as shown in Figure 3.2.

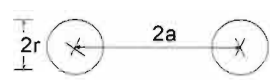

Figure 3.2 : A single pair of cables

The propagation of a signal along this pair, can be described using the following four parameters

i. Capacitance determines the cable's capacity to store electric energy which is expressed as C, in units of farads per meter
ii. Current flowing along the conductors generates a magnetic field, with the strength controlled by the cable inductance, L, in units of Henries per meter
iii. The dissipation of energy is denoted by resistance, R, in units of ohms per meter
iv. The dielectric between the two conductors has a small conductivity, G, in units of Siemens per meter which also dissipates energy.

To obtain the accurate estimations on these parameters, any other cable surrounding the pair is assumed to be an equivalent insulator. It is assumed that any frequency greater than 100 kHz is a high frequency.

3.1.2 Single Pair Capacitance

In access networks the capacitance of the cables is usually 45nF/km [23]. The general equation for the capacitance per unit length of a single pair is given by

$$C = \frac{\pi \varepsilon_0 \varepsilon_r}{\ln\left(\frac{2a}{r}\right)} \quad \text{F/m} \tag{3.1}$$

Where r is the radius of the conductor, ε_r the relative permittivity, ε_0 the permittivity of free space, and $2a$ the distance between the two conductors. This equation shows that cables with large diameters or low wire gauges have more capacitance.

3.1.3 Single Pair Inductance

The inductance of a single pair is given by

$$L = \frac{\mu_0}{\pi} \ln\left(\frac{2a}{r}\right) \text{H/m} \tag{3.2}$$

Where μ_0 is the constant free space permeability.

This equation shows that cables with low wire gauges have less inductance, which means less dissipation of power.

3.1.4 The Skin Effect

Skin effect is one of the factors that determine the level of crosstalk of conductors with the other conductors in a bundle. The skin depth is given by

$$\delta = \frac{1}{\sqrt{\pi f \mu_r \mu_0 \sigma}} \tag{3.3}$$

Where f is the frequency in kHz, σ is the conductance of the conductors and μ_r the relative dielectric constant. For copper conductors, the skin depth is given by

$$\delta = \frac{2.11}{\sqrt{F_{kHz}}} \text{mm}$$

Example: For F = 4 kHz which is an upper band frequency for voice transmission.

$$\delta = \frac{2.11}{\sqrt{\frac{4\times10^3}{1000}}} = \frac{2.11}{\sqrt{4}} = 1.06\text{mm}$$

For F = 512 kHz which is maximum down stream transmitting frequency for splitterless ADSL (ADSL-Lite)

$$\delta = \frac{2.11}{\sqrt{\frac{512\times10^3}{1000}}} = \frac{2.11}{\sqrt{512}} = 0.09\text{mm}$$

For F =12MHz, which is a maximum downstream transmitting frequency for VDSL [7]

$$\delta = \frac{2.11}{\sqrt{\frac{12\times10^6}{1000}}} = \frac{2.11}{\sqrt{12\times10^3}} = 0.019\text{mm}$$

The above results show that for higher frequencies the skin depth is thin, and for lower frequencies the skin depth is thicker. That shows that at high frequencies, the current flows in the outer part of the conductor, which creates a condition for increased crosstalks.

3.1.5 Single Pair Resistance

The resistance per unit length is given by

$$R_c = \left\{ \frac{1}{\sigma\pi r^2} \right. \text{ for } \delta >> \text{r (low frequencies)} \tag{3.4}$$

$$= \left\{ \frac{1}{2\sigma\pi r^2} \right. \text{ for } \delta << \text{r (higher frequencies)} \tag{3.5}$$

The sum of the unit resistances per unit length of the conductors gives the resistance per unit length of a pair. That means the resistance per unit length of a pair is given by

$$R = 2\times R_c = \begin{cases} \dfrac{2}{\sigma\pi r^2} & \text{for } \delta >> \text{r and} \end{cases} \quad (3.6)$$

$$= \begin{cases} \dfrac{1}{\sigma\pi r^2} & \text{for } \delta << \text{r} \end{cases} \quad (3.7)$$

From Equation 3.6, it can be seen that a pair has twice the resistance of a single conductor. Although that is the case, the resistance of these conductors at DSL frequencies is so small to such an extent that it can be neglected.

3.1.6 Propagation Constant

The propagation constant of a transmission line is defined as

$$\gamma = \sqrt{ZY} = \sqrt{(R + j\omega L)(G + j\omega C)} \quad (3.8)$$

$$= \sqrt{(R + j\omega L).j\omega C}$$

$$= \alpha + j\beta$$

Where α is the attenuation constant in Neper/km and β is the phase constant in rad/km. For high DSL frequencies, R<<ωL and G<<ωC, the propagation constant becomes

$$\gamma = \omega\sqrt{LC} \quad (3.9)$$

Neper can also be given in dB i.e.

$$\alpha_{dB} = \frac{20}{\ln(10)}\alpha = 8.69\alpha \quad (3.10)$$

3.1.7 Characteristic Impedance

Another important parameter is the characteristic impedance of the transmission line in units of ohms. The characteristic impedance of a single conductor is given as

$$Z_0 = \sqrt{\frac{Z}{Y}} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \quad (3.11)$$

As it has been mentioned earlier, for twisted pair transmission lines, $G \approx 0$, therefore

$$Z_0 = \sqrt{\frac{Z}{Y}} = \sqrt{\frac{R + j\omega L}{j\omega C}},$$

For DSL transmission, the frequencies are high, and therefore $R << j\omega L$ which implies that

$$Z_0 = \sqrt{\frac{j\omega L}{j\omega C}} = \sqrt{\frac{L}{C}} \tag{3.12}$$

In the scenario of ADSL frequency signals, the approximate value for the characteristic impedance is equal to 100Ω resistive and for VDSL that is equal to 135Ω resistive.

3.1.8 Attenuation Constant

This is one of the great threats in transmitting DSL signals over long loops. At high frequencies, where $R << \omega L$ attenuation constant is given as

$$\alpha = \frac{R}{2}\sqrt{\frac{C}{L}} + \frac{G}{2}\sqrt{\frac{L}{C}} = \frac{R}{2}\sqrt{\frac{C}{L}} = k_1\sqrt{f} \qquad \text{, with } k_1 = \frac{R}{2} \tag{3.13}$$

Substituting equation 3.12 in equation 3.13 yields

$$\alpha = \frac{R}{2Z_0} \tag{3.14}$$

At low frequencies where f<10 kHz or $R >> \omega L$

$$\gamma = \sqrt{j\omega CR} = (1 + j)\sqrt{\frac{\omega CR}{2}} \tag{3.15}$$

$$\therefore \alpha = \sqrt{\frac{\omega RC}{2}} = k_2\sqrt{f} \approx 0 \qquad \text{, with } k_2 = \sqrt{\pi RC} \tag{3.16}$$

Equation 3.13 shows that attenuation is proportional to the frequency. As the transmitting frequency increases, attenuation also increases. Low AWG cables have lower attenuation levels than those with high wire gauges. Attenuation increases with increase in distance. This shows that for transmitting over long distances, transmission frequencies must be low, and the selection of small wire gauges is necessary. It can now be concluded that some of the parameters that dictate the DSL system design are frequency, distance, and wire gauge.

3.1.9 Reflection Coefficient

This parameter is crucial in the DSL line qualification. When the signal with voltage, V_i is transmitted down the transmission line, at the end of the cable a portion of the voltage is reflected. The reflected amount of voltage, V_r, depends on how the end of the line is terminated. The reflection coefficient is denoted by ρ, which is given as

$$\rho = \frac{V_r}{V_i} \tag{3.17}$$

According to the electromagnetic wave theory, the solution of the wave equation contains the term

$$\rho = \frac{(Z_T - Z_0)}{(Z_T + Z_0)} \tag{3.18}$$

which is the reflectivity due to a load impedance mismatch. Rearranging terms, gives

$$Z_T = Z_0\left(\frac{1+\rho}{1-\rho}\right) \tag{3.19}$$

For various pure resistive terminations, $Z_T = R_T$. When $Z_T = Z_0, \rho = 0$, which means there is no reflected voltage. For an open circuit, $Z_T = \infty\Omega$ and $\rho = +1$. For a short circuit, $Z_T = 0\Omega$ ohms and $\rho = -1$. These equations also hold for connections of lines to other transmission lines of different characteristic impedances, which is the case in the loop plant, where a number of miscellaneous AWG cables make a loop. With this information what will happen can be predicted if there is an open line (bridged tap) extending from a line between the DSL subscriber and the central office, and a scenario where there is a short circuit in the subscriber loop, either by water or two wires in contact. This will be discussed in detail in loop qualification.

3.2 Drivers for DSL Loop Qualification

High-speed DSL services can be supported on ordinary copper telephone lines already installed in commercial and home buildings. Existing copper twisted-pair telephone lines become the access paths for the multimedia and data communications that customers are demanding. This is a great advantage as it eliminates the need for major investments for network upgrade. If copper could not be used, this would require alternative and expensive architectures such as fibre to the home (FTTH), hybrid fibre/coax, etc. Although using the existing network is a great advantage, there are a number of deployment challenges associated with the existing loop plant. Advanced engineering skills are necessary to avoid unnecessary delays and high deployment costs associated with incorrect predictive loop qualification.

The quality and design of the loop plant dictates the performance of DSLs. This creates a need for determining if the loop is able to transmit xDSL signals. This will mean the provisioning of reliable services with high revenue generation and customer satisfaction. Improper loop prequalification can result in customer-initiated trouble reports, and the uncontrollable endless fault fixings by technicians. Poor quality loops degrades the performance of DSL services, with some services not being able to work at all. Developing countries need a solution that helps to quickly overcome the challenges of service assurance so as to ensure fast deployments in this technology. This creates a challenge for the investigations of DSL solutions that help to quickly overcome the challenges of service assurance. A solution must be able to provide cost-effective and reliable techniques that can be used to pre-qualify the loop, install services, and assure their continued availability. This section adds great value towards this goal.

3.3 Local Loop Sections

3.3.1 Feeder Plant

Within the central office (CO), cables from switching and transmission equipment are terminated at the main distributing frame (MDF). MDF allows the subscriber line to be connected to any port of any equipment in the CO. The cables at the MDF have large diameters. The number of the CO lines depends on the location of that particular CO. COs that are found in large cities may carry up to 100,000 lines [12]. These lines are contained within a protective polyethylene sheet. These wires are in pairs. In some countries these wires are in units of four, which creates the disadvantage of service crosstalks. From the main distributing frame are the feeder cables that lead to the serving area interface (SAI), which serves a number of customers depending on the location. In areas with high subscriber density this can be anything between 1,500 and 3,000 lines. These cables are often underground cables. Therefore a subscriber loop has three sections, that is feeder cable, distribution cable and drop wire.

3.3.2 Digital Loop Carrier Design Standards

A digital loop carrier (DLC) may be defined as an electronic multiplexing device that is found on the serving area interface (SAI) point. This can multiplex up to 96 lines into a few T1-carries feeder lines to the CO. A new DLC known as a fibre-fed next generation digital loop (NGDL), can terminate up to 2.000 customer lines.

3.3.3 Carrier Service Area Design Rules (CSA)

These rules are used for designing a loop plant that is serviced by DLCs. According to CSA design rules, a maximum CSA loop length must be 3.7km for loops that are designed only from 24 AWG (American Wire Gauge), and a maximum of 2.75km for loops designed from only 26AWG. The maximum loop resistance made from a mixture of different wire gauges must be 850 ohms. A bridged tap must have a maximum cumulative length of 762m. The total loop length is reduced by the cumulative length of a bridged tap on that loop.

3.3.4 Distribution Plant

Distribution cables contain 25 to 1000 pairs. Each customer is served by a drop wire that is extended from the distribution cables. The distribution cable connects to drop wires via a distribution terminal, which typically serves four to six units. About two to four pairs of

22 AWG pairs are contained in typical drop wires. The feeder and distribution cables are bundled into binder groups of 25, 50, or 100 pairs. The pairs within the binder group remain adjacent to each other. The crosstalk between pairs in different groups is less than the crosstalk of pairs within the same binder group. As the distance away from the CO towards the customer increases, the number of pairs decreases due to the branching of some lines to the distribution points. Figure 3.3 shows a typical subscriber loop structure.

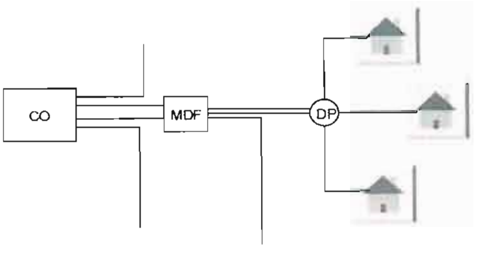

Figure 3.3 : Subscriber loop structure

3.3.5 Wire Gauge and Loop Resistance

Loop plant is designed according to the rules that can vary from country to country. A rule called 1300-Ohm resistance is used in United Sates of America (USA). This rule states that the first 3.05 km of cable from the CO must be 26 AWG, beyond this point, high gauge wire can be used to avoid excessive loop resistance. The overall plant must be made of the equal amounts of AWG, e.g. 24 and 26 AWG, and amounts of buried and overhead wire must also be approximately equal. Very long loops will have some 22 or 19 AWG so as to combat losses due to high resistances. Connecting one wire gauge to a different wire gauge can result in impedance mismatch, which results in signal reflections. This cannot be avoided in a loop plant but the level of reflected voltages must be reasonable. Loop design principles show that long loops have got more different sets of wire gauges. DSLs with echo chancellors can perform better even on lines with these impedance mismatches. Table 3.1 shows the different AWGs with corresponding resistances and diameters.

3.4 Loop Qualification

3.4.1 Objectives

i. To optimize usage of copper infrastructure
ii. To identify the type of DSL system and the bit-rate that can be successfully and reliably provisioned on a given customer's loop
iii. To ensure the proper provisioning and function of physical line between the subscriber and serving Central office in the least amount of time with a better quality of service
iv. To locate and clear faults, that are capable of blocking the high frequency DSL signals.
v. To avoid unsuccessful and expensive deployments.
vi. To ensure the proper and efficient spectrum management that complies with the standards, so as to take care of the future installations of other new DSL systems.

3.4.2 DSL Loop Qualification Techniques

There are two major techniques that are used for DSL loop qualification testing, single and double-ended technique.

3.4.2.1 Single Ended Testing Technique

DSL loop qualification here is achieved by setting equipment only at the Central Office (CO). This does not require a technician at the customer's premises. This test provides information on necessary loop repairs. This test provides a confidence of 90 to 95 percent of checking if the loop is able to support DSL services [27]. One approach to the single-ended DSL qualification solution involves current loop testing, operational support system, and use of plant records. The operational support system will measure loop length and rely on plant records for both current and previous cable routings to check if bridge taps and load coils are present. Using the single ended testing techniques and plant records alone might not be sufficient to qualify a copper loop. Ideally, for more reliable testing there is a need for both single and double ended technique. The information captured on this test will be used to determine which subscribers can be offered DSL services, and to estimate the amount of work required to condition the local loops to support DSL in case of customer request. The service provider will also know if a particular customer's line can support DSL transmission for voice or data services. The following tests can be performed using single ended testing: -

a) Load coil detection
b) Measurement of line length
c) Detection of bridged taps
d) Metallic tests and longitudinal balance
e) Verify acceptance criteria for future installations
f) Locate water in the bundle
g) Wideband noise measurements

a) Load Coil Detection (LC)

Equation 3.1 showed that the capacitance of a line is given in *F/m*. That means the equivalent capacitance is given by the product of *F/m* and loop length. This indicates that long loops suffer from the attenuation of voice signals due to high capacitance. To combat these attenuations load coils (LC) were placed between the customer and the Central Office. The first LC will be placed at a distance of 0.9144Km from the CO with subsequent LCs placed at constant intervals of 1.288Km, as seen on Figure 3.4.

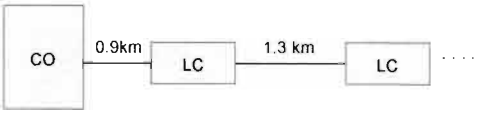

Figure 3.4: Load coil placement

LCs were normally placed in loops longer than 5.5Km. These loops usually use 19, 22 and 24 AWG [28]. The design rule says no subscribers should be placed between the loading coils. Load coils act as low pass filters in a line with a cut-off frequency just above the voice frequency signals. This will result to a scenario where only the signals within a bandwidth of 300Hz to 4 kHz are being allowed to go trough. Any signal above 4 KHz will be discarded. This makes it impossible to transmit high frequency DSL signals over such loops. Because of that reason, load coils need to be removed before deploying any DSL service. It has been claimed that some DSLs cannot be affected by load coils. This has not been supported enough and does not make any sense so far. Another popular load coil placement method is Revised Resistance Design (RRD). RRD specifies that all loops longer than 3.048Km must be loaded. A code letter defines the loading arrangements that specify the distance between the loading coils, and a number defines the inductance value. The H88 and the D88 loading standards are one of the standards that would make this easy if they were properly followed. The number *88* refers to the inductance in milli-Henrys (mH) of the actual loading coils; H is the designation for 1.8Km spacing between coils, and D indicates 1.4Km spacing.

Unfortunately, previous researches show that not all the loaded loops are loaded within these specifications. This is a result of frequent changes that take place in the loops during the maintainace and introduction of new services. A good example of this nature is the introduction of the Digital Loop carriers (DLC). These leads to a need for more effort to locate these bridged taps. This introduces a number of technologies that can be used to accomplish this goal. Table 3.2 shows some guidelines that need to be followed when designing a loop.

Table 3.2 Loop Design Guide

Design Parameter	Modified Long Loop Design
Loop Resistance	1501-2800Ω
Loading	88mH (LC)
Cable Gauge	Two gauge combinations 22,24,26 AWG
Bridged Tap	Total BT length 3.7km

b) Loop Length Distribution

This is about positioning the customers from the CO. The average distance between customers and the COs differs from country to country. In UK and US, 50%, of the customers are within 2km range. In their loop plants, business loops tend to be shorter and residential loops tend to be longer.

- **Line Length Measurement**

The length of the local loop is one of the factors that affect the performance and the data rate of the DSLs. Long loop DSLs usually suffer from unacceptable attenuations. The received signal power is inversely proportional to the loop distance. As it has been already mentioned, the tolerance level of conductors to external electromagnetic fields decreases when the line length increases. It is therefore a requirement for xDSL service providers to know the distances between their customers and the central office. This will help on identifying the kind of DSL service that can be delivered over that particular loop. To calculate the loop length, Equation 3.20 can be used.

$$L = \frac{ct}{2} \qquad (3.20)$$

Where c is the propagation constant, t the time required for receiving the echo from the test pulse that has been down the line and L the length of the loop. Another loop length testing technique uses tip-to-ground and ring-to-ground and tip-to-ring capacitance measurements. The loop length is calculated using 0.083μF/mile [26]. This is due to the fact that it is easy to control the capacitance in a loop. It depends on the twist of the wires and capacitance varies 6% from 0.078 to 0.086μF/mile, with a normal value of 0.083μF/mile.

c) Bridge Tap (BT)

It has already been seen that feeder cables provide links from the central office to concentrated customer areas. From the feeder cables to the customer premise are the distribution cables. Some of these distribution cables are connected and left hanging so as to respond fast to any service customer request. Some of them will be connected to the customers and some will remain hanging. These unterminated lines are referred to as bridged taps (BTs). Although the BTs have got no effect on voice transmission, they still form another potential problem for DSL frequency transmission.

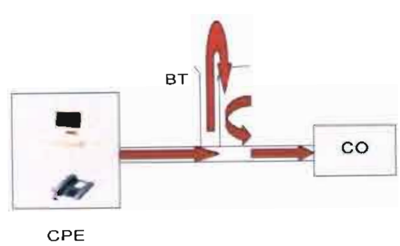

Figure 3.5: Bridged tap scenario

Occurrence of bridged taps in the network is not that easy to control. The reason is that some of the bridged taps occur as a result of the changes in customer requirements. Some of the modifications and repairs leave some parts of the lines connected, but not in use. Sometimes it is more cost-effective to install new lines than repair damaged lines.

- **The Effect of Bridged Taps on DSL Systems**

These unterminated lines result in impedance mismatch and high return loss. When the signal is transmitted down the main pair, the signal power splits between the main path and the bridged tap. When this signal reaches the unterminated end of the bridged tap it is reflected back, thus introducing noise to the main cable as seen on Figure 3.5. These unterminated lines will also pick up radio and any other form of broadcasting signals. The length of a BT also makes a big difference. Long bridge taps result in more attenuation and pick up more disturbances than the shot bridge taps. The length of bridge taps impacts the performance of each xDSL differently. The mean bridge-tap length is only 0.4Km, which will not significantly impair xDSL performance. The worse case bridged tap is a heavy-gauge tap of a length that equals to one quarter of the wavelength of any used transmission frequencies causing an additional loss of 3 to 6dB. The reflections from a quarter wavelength tap are 180 degrees out of phase from the primary signal frequency and thus partly cancel the signal. DSLs can tolerate multiple bridged taps, provided that the combined signal loss due to loop length and bridged taps is within the system's loss budget. The HDSL and ISDN transmissions will typically tolerate 1.8Km of bridge tap in copper line, but they can reduce the bandwidth and speed of transmission. With the current trend towards offering lower-speed ADSL/RADSL-based services in the range of 384/384 kbps to 1544/384 kbps, the effect of bridge taps has been reduced. Many DSLs have got adaptive equalizers and echo cancellers, which partially reduce the transmission impairments caused by bridged taps.

d) Longitudinal Balance Testing

Long loops are more exposed to noise than short loops. This is because of the decrease in the level of withstanding the noise from the external electromagnetic fields. Since the signals travel for a long distance they can be easily corrupted by any external strong interferers. As a result of that some measures need to be taken to combat the corruption of the signals carried over these cables.

Measuring of electromagnetic field tolerance over balanced lines is referred to as the longitudinal balance. The ideal balanced lines are not affected by any external electromagnetic fields, as they are designed such that they cancel any noise of such nature. In real situations, balancing the lines can only decrease the interference levels but not completely eliminate it. Because of that there is a need for measuring longitudinal balance, as some of the DSL technologies cannot tolerate a certain level of electromagnetic field interferers.

• **Metallic Test**

Pre-qualification testing should include standard metallic fault testing. The general quality of the outside plant can be determined with the standard *tip-to-tip ring (T-R), tip to tip ground (T-G), and ring –to ground- (R-G)* parameters. Unbalanced circuit caused by unbalanced longitudinal currents or power-line harmonics can cause crosstalk noise, causing bit errors that result in slower xDSL transmissions.

e) Crosstalk

Sources of noise in DSL systems can either be thermal or any other kind of source. Crosstalk is the unique noise of its kind as it is caused by the presence of other transmissions in the same binder group. There are two kinds of crosstalk noise that are a threat to DSL transmission systems, that is near end crosstalk (NEXT) and far end crosstalk (FEXT). NEXT can be defined as the noise that results from the near-by transmitting source, leaking into a neighbouring receiver through the coupling between pairs. FEXT can be defined as the noise resulting from a source and multiple sources coupling into another pair and appearing at the far end along with the desired signal of that pair. Figure 3.6 shows the example of occurrence of NEXT and FEXT.

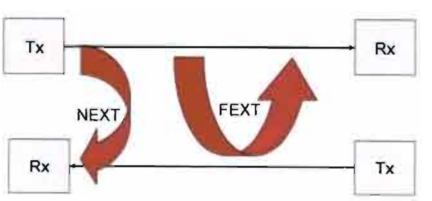

Figure 3.6: Crosstalk

Both NEXT and FEXT are normally partitioned into three noise categories, 200 kHz noise, which impairs the performance of all 2B1Q code DSL transmission (ISDN, SDSL, and HDSL), noise up to 1,1MHz, which degrades the performance of ADSL services; and the presence of T1, which significantly impairs ADSL. Wideband noise measurement can help to isolate DSL transmission problems. Noise measurements up to 1.1 MHz will be required to determine if a loop can support ADSL transmission. The identification of T1 circuits or other DSLs can be determined by looking for their characteristic frequencies on the loops. Another cost effective method is to exploit the fact that crosstalk always degrades the bit error rate (BER) of the DSL system, and do the BER test. For the qualifying loops, the BER must be at acceptable levels. The time taken to complete the test is crucial. The test duration depends on the desired transmission rates on the loop under test. Table 3.3 indicate the BER for the data rates 1.544 Mbps<f<6 Mbps for a Cable Shark line qualifier [27].

Table 3.3: Transmission rates with equivalent test durations

Desired transmission rate	Test duration
1544kb/s <	20 min
6Mb/s >	100s
1544Mb/s	500s

For this test to be done, a DSL signal generator is placed at the central office (CO), with the BER meter on the customer premise (CP) side. If the test is done on the ATM level, there is a need for generating ATM traffic both up and down stream, with the BER meter measuring the received BER at both ends.

3.4.2.2 Double Ended Testing

This technique requires test equipment at both ends of the copper loop. A Technician is needed to install modem or test equipment at the customer location that communicates with the reference modem in the CO and a device connected to the customer's network interface device (NID). If the service is not operating, a work order is issued to service the line. However, using a reference modem may not provide sufficient information as to why the loop will not support DSL transmission and may need work prior to initiating service. Because of extra expenses associated with sending a technician, this technique tends to be more expensive.

3.4.3 Time Domain Reflectometry Testing (TDR)

Time domain reflectrometry (TDR) is a cable testing technique that locates the cable impairments by transmitting a pulse down the cable. A pulse is reflected back from any deformation or impedance mismatch that is encountered. The impedance mismatch may be caused by cable problems such as bad connections, a cable fault or the unterminated end of the cable. The travel time of each reflection uniquely determines each cable fault's location. Additional information can be obtained by analysing the sign, length, and amplitude of a TDR reflection. The reflected pulse is sampled by the TDR and displayed as a waveform on the screen of the instrument. If the conductors are manufactured with exact spacing and the dielectric is exactly constant, then the cable impedance will be constant. If the conductors are randomly spaced or the dielectric changes along the cable, then the impedance will also vary along the cable. A TDR sends electrical pulses down the cable and samples the reflected energy. Any impedance change will cause some energy to reflect back towards the TDR and will be displayed. The level of change of impedance is determined by the amplitude of the reflection. Matching the impedance of the instrument to that of the cable under test will help reduce unwanted reflections; however, the distance accuracy of the instrument is not affected.

3.4.3.1 Impedance

Any time two metallic conductors are placed close together; they form a transmission line, which has characteristic impedance. A TDR looks for a change in impedance, which can be caused by a variety of circumstances, including cable damage, change in cable type, improper installation, and even manufacturing flaws. The insulating material that keeps the conductors separated is called the cable dielectric. The impedance of the cable is determined by the conductor diameter, the spacing of the conductors from each other and the type of dielectric material or insulation that is used to separate the conductors.

There are a variety of transmission lines that can be interrogated using TDR. These include parallel wire cables and coaxial cables.

3.4.3.2 TDR Reflection Coefficient

Time domain reflectometry test is one of the tests that are useful during the copper qualification stage and also for fault location during maintenance and repair periods. The reflection observed with a TDR cable tester depends on several factors, including the type of cable fault. Faults are basically changes in the transmission line properties (R, C, and L), which are measured as changes in impedance (Z) using TDR. It is assumed that the TDR unit sends a step voltage pulse of magnitude V. When it reaches the end of the cable, some of the voltage is reflected. The reflected voltage, V_r is displayed by the TDR unit as the reflection coefficient, ρ, which is defined in Equation 3.18. TDR makes use of the previously explained transmission characteristics of the twisted pair.

TDR can be used to estimate the length of the line. If the line ends with short-circuit, the polarity of the reflected pulse is inverted; if the circuit is open there is no change in the polarity of the signal. The polarity of the reflected signal depends on the sign of the reflection coefficient.

3.4.4 Other Impairments for xDSL

For analogue voice frequency signals, normally the attenuation based on the wire diameter determines the length of the subscriber loop. For digital signals with bandwidths exceeding voice frequencies, normally attenuation, crosstalk and phase delay limit subscriber loop lengths. The impairments that high-speed digital services must deal with on the copper loop need to be well understood. The impairments at these frequencies fall into two main categories, physical and electrical. Physical impairments arise from the local loop being engineered and optimized for analogue voice. Splices between different wires bend and flex in the wind, causing instantaneous *micro-outages*. And splices are not always done properly amongst pairs within the same bundle. Although each pair is colour coded, various factors make it possible to splice together wires from separate pairs. Such split pairs are seldom fatal for voice, but a real problem for digital services. Short but untwisted drop cables to the premises had minimal effect on overall voice quality, but are a concern in xDSL environments. The use of proprietary line extenders and digital loop carrier (DLC) pose additional problems for DSL, mainly due to their operation only in the voice passband. DSL deployments would have been a walk-over if measures were taken when designing the original copper access infrastructure to provide *universal service* and easy conversion to services like DSL. As it has been mentioned on chapter one that the remote areas are more often served by public phones on shorter loops, and there are fewer local exchanges per square area. Load coils are rare on such access lines outside, and bridged taps are more often the result of installation oversights than of systematic planning. Electrical loop impairments are also called interferers or disturbers.

3.4.4.1 Network Components Noise

There are DSL network components that contribute to the noise found in DSL systems. Thermal noise is one of the other sources of noise. This is because of the heat that is generated by the powered components. These components reside in the cable infrastructure but can impair the operation of DSL systems. These include surge protectors, radio frequency interference (RFI) filters, the cable infrastructure, which exhibits faults such as split pairs, bunched pairs, leakage to ground, low insulation resistance, battery or earth contacts, and high-resistance joints. The noise sources mentioned above can be classified as capacity or performance limiting. Capacity limiting noise is usually slowly changing, such as thermal noise and crosstalk. These noise levels are often predictable and relatively easy to take into account during the deployments. Sophisticated DSP methods have been developed and implemented in order to deal with these kinds of noise problems in DSL systems.

3.4.4.2 Impulse Noise

Impulse noise is the result of the electromagnetic events that occur very close to the telephone lines. Examples of impulse generators include noise from AC motors, control voltages to elevators and ringing of phones on lines sharing the same binder, lightning strikes, electric fences, power lines, arc welders, switches, fluorescent lighting, and so on. Each of these effects is instantaneous and results in injection of noise into the phone line through the same basic mechanism as RF noise ingress, but typically at much lower frequencies, induced voltages are typically a few millivolts, but can be as high as 100mV [7]. Such voltages may sound small, but the severe attenuation of high frequencies on twisted pair means that an impulse can appear as an actual transmitted signal to the receiver. Typical impulses last 10s to 100s of microseconds but can increase time intervals up to 3ms. Numerous studies of impulses have resulted in both analytical models for impulses based on statistical analysis of over 105 impulses by various groups. Impulses are so diverse such that its measurement purposes remain with some bias. The most widely used analytical impulse model is the Cook pulse. Cook recovered over 105 impulses. The ADSL standard, however, uses two measured impulses instead of the Cook pulse.

3.4.4.3 RF Noise

This is another factor that degrades the xDSL-transmitted signals. Noise can result to a complete distortion to low power-transmitted signals. The source of noise can be random thermal noise and Radio emissions from sources such as AM or HAM radio being the most potential source of noise that can result to signal degradation. Analogue cellulars are also potential sources of noise. These emissions are coupled to the pair as longitudinal balance or common mode noise. Radio frequency (RF) signals interfere with the signals on twisted-pair phone lines, especially aerial lines. Phone lines, being made of copper, make relatively good antennae with electromagnetic waves incident on them leading to an induced charge flux with respect to earth ground. The common mode voltage for a twisted pair is for either of the two wires with respect to the ground - usually these two voltages are the same because of the similarity of the two wires in a twisted pair. Thus well-balanced phone lines should see a significant reduction in differential RF signals on the pair with respect to common-mode signals. However, balance decreases with increasing frequency, and so at frequencies of xDSLs from 560 kHz to 30MHz, xDSL systems can overlap radio bands and will receive some level of RF noise along with the differential xDSL signals on the same phone lines. This type of xDSL noise is known as RF ingress. Many amplitude modulation (AM) radio stations broadcast in the same range as DSL methods operate. Aerial wires are much more at risk, especially in areas where AM stations are particularly dense. Even amateur radio can be a concern for DSL schemes that operate on aerial cable above 1 MHz [29]. The noise level can be quantised by measuring the RMS value or by its power spectrum. This is convenient if the power spectrum of the noise is constant over all frequencies of interest. Lines with undesirable noise interference sources must be isolated for this to be effective.

3.4.5 Propagating Loss

This is a loss that occurs in the cable and it varies as a function of frequency. Attenuations increases with the increase in frequency. This hinders high frequency transmissions over long lines. Propagation loss has got the potential of reducing the data rate for multi rate services as well as reducing noise margins for fixed-rate DSL.

3.4.6 The Return Loss

To maximize the power from the source to the transmission line, the impedance of the generator must match that of the line. Impedance matching is also necessary to maximize the power in the load. Mismatch can result to power loss at the receiver end, and that results to transmitter performance degradation. The existing loop plant contains a number of different wire resistance gauges. A change in a wire gauge may be seen as an impedance mismatch. Different wire gauges provide different data rates at different distances. Rate Adaptive Digital Subscriber (RADSL) makes it possible to provide data rates according to the level of quality and length of the loop. This creates opportunity for covering customers located at long and poorly designed loops. This can be done by providing the low data rate services to these customers. Equation (3.21) defines the return loss. When the load is not receiving any power this power is reflected back to the transmitter.

$$L_{ret} = 10\log\frac{P_i}{P_r} \tag{3.21}$$

For the return loss, the TDR tester displays the reflected negative pulse, if the nominal impedance is greater than the new impedance detected by the transmitted testing pulse.

3.4.7 Installation Testing

This is done in scenarios where there is a possibility of a line being able to support the xDSL services. A customer is given a plug and play xDSL modem for personal installation. If the line is not working, a technician is dispatched either to the customer premises or Central office for performing a pre-loop test. This method is not highly recommended as its disappointments can irritate customers who are desperate for services.

3.4.8 Post-Installation Support Testing

This refers to the follow up after installing the xDSL services. A number of factors can affect the performance of xDSL at early stages of installation. All the hardware and the software components housed in the central office collocation cage must be verified, Cabling between DSLAM ports/ ATM channel/ PPP and either the intermediate distribution frame (IDF) in the CO.

3.4.9 Fault Troubleshooting

This is facilitated via the test system's software, allowing tests to be routed to the proper test device. Advanced systems even suggest what tests should be run and where to start troubleshooting problems. It is highly beneficial during fault isolation to have historical results from the initial prequalification available for reference. Another source of failure of already deployed DSL lines is the presence of water in the bundles. This can be experienced after rains if the cables are not water protected. TDR testers do this test by displaying ripples in the reflected signal associated with water. Some testers show repeatedly charging effect associated with water and resistance ground to ground measurement, which show trickle of current conducted by water.

3.4.10 Centralised Testing

The Loop-Care has come up with a system that is able to centralise and automate the installation testing, helping in making the right decisions and ensure that the customers receive top service quality right from the first day of operation [30]. The system tests spectrum compatibility in the loop and at the central office, it does not only measure and identify noise, but also detects bridge taps that can hinder service availability. It can also confirm the existence of service by detecting and verifying the standard asymmetric DSL (ADSL) maintenance signatures on the loop. Further tests can estimate, verify, and recommend actions to optimize data rate in the loop. The tests run automatically and sequentially, with the results of one test determining which other tests need to be run. DSL problems can be diagnosed with a single query using the sophisticated analysis algorithms. Faster and more reliable results are achieved with less test equipment. This system is able to store a lot of updated information for re-verifying loops suitability at all times. Web based GUI simplifies operations and helps troubleshoot problems that need manual intervention. The end-result is a cost-effective verification of DSL services and thus satisfied customers. Such testing systems are highly recommended for Developing countries as they minimise the costs associated with unsatisfied customers during the early deployments.

3.4.11 Broadband Test

Importance of Loop Data Capturing:

This considers both residential and business customers that are served by twisted cable pairs. The subscriber loops needs to be well understood by the operator. This will reduce the unnecessary delays for the new service requests by customers. This becomes easier if the loop make up records are available. This involves knowing things like plant flexibility points such as junction boxes etc. There are loop test equipment manufacturers that offer measurement devices that can store data using a remote craft dispatch and two ended testing.

3.5 Conclusion

Deploying DSL services without using the sophisticated loop qualifying techniques can look cheaper but it ends up the most expensive. A number of companies have developed the required cable testers. Some of these testers can display both graphic and decimal format loop information. Figure3.7 shows some results of a load coil test from the tester manufactured by Conso Electronics.

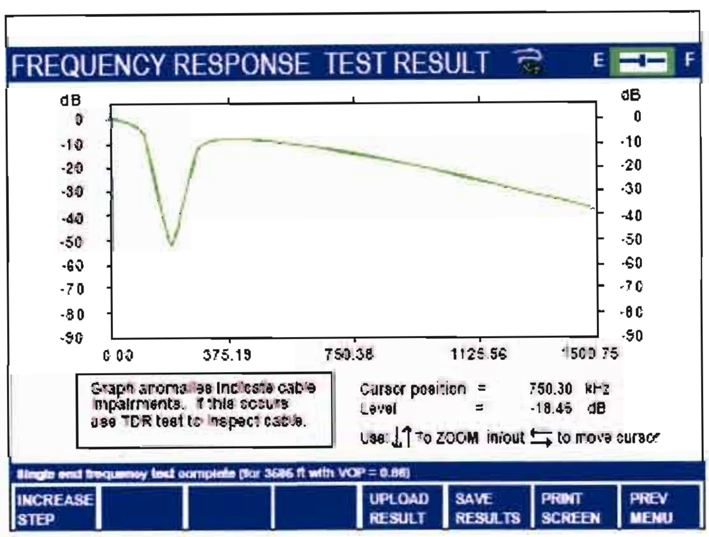

Figure 3.7: Typical load coil test results [31]

Single ended is the cost effective technique for qualifying loops as it needs no customer visits. A test of a number of loops is done at the single point which is the central office. This means significant savings in the rural areas as it is costly to travel in such environments. RADSL is the only technology that can be deployed without intensive loop qualifying tests. The reason is that this technology can deliver data rates depending on the quality of the loops. If the rates are reasonable for the applications required by that particular customer, this technology can be provisioned.

Chapter 4

Spectral Management in DSL Systems

4.1 Crosstalk Analysis

In Chapter 3 crosstalk has been identified as the main factor that affects the performance of DSL technologies. Crosstalk results in the corruption of a number of symbols at the receiver. Crosstalk occurs within wire pairs contained in the same binder group and also with the pairs in the neighbour binder. Insufficient cable shielding, excessively large disparity between signal levels in adjacent circuits, unbalanced lines, and overloaded carrier systems contribute to the level of crosstalk. Standard telephone wiring provides some protection from signals on nearby pairs. In the ideal scenario, with capacitance perfectly balanced between each wire in the pair and the rest of the cable, all disturbing signals are coupled equally and the resulting noise signal is zero. However, even with the highest quality cable, this protection has physical limits, allowing some signal bleed to occur between different services. The level of crosstalk between different services also depends on the line coding used. Services that do not incur severe crosstalk on each other are referred to as spectrally compatible. Knowing the spectral compatibility will help in identifying, which services can be, placed in the same binder group. This chapter takes a closer look at the parameters that contribute to the level of crosstalks in the DSL systems, identifying the services that are spectrally compatible and the services that are not.

4.1.1 Power Levels in DSL Systems

As explained in the previous chapters high transmission frequencies of DSLs results in high attenuations compared to any other services like voice, fax and analogue data services. One of the solutions, for working against attenuations is to increase the DSL transmission power levels. This would improve the Bit Error Rate (BER), thus overcoming attenuations and allowing long distance transmissions. However, increasing the power levels will create a platform for crosstalk. DSL transmits at +15 to 20 dBm in order to recover the signal at the receiver located at a distance not greater than 6km.

4.1.2 Near End Crosstalk (Next)

NEXT manifests when the DSL receiver is affected by coupled noise from transmitter(s) at the same end of the cable. This happens mostly in DSLs using the same frequency bands for transmission in both directions. The signal from the transmitter is coupled back into the receiver. NEXT between two pairs of the same Transceiver can be avoided by using FDM or TDM. FDM does this by dividing upstream and down stream DSL-transmission into two different channels. At higher frequencies, NEXT noise will increase, while the signal power will decrease due to attenuation in the cable.

4.1.3 Far End Crosstalk (FEXT)

FEXT manifests when the receiver is affected by coupled noise from transmitter(s) at the other end of the line. FEXT is more experienced in DSLs using separate frequency bands in the same direction of transmission. Signal power drops as it travels down the line. That means FEXT takes place at a distance at which the signal power levels are low. Due to that reason, FEXT will always be less corrupting compared to NEXT.

4.2 DSL Power Spectral Densities (PSD)

The level of crosstalk in an xDSL system depends on the spectral density of the disturber. This section considers ADSL, ISDN, SHDSL, and T1 as potential disturbers. This results in a need for evaluating the power spectral densities of these disturbers [33, 34].

4.2.1 ADSL Upstream PSD

The transmit upstream power single side spectral density of an ADSL is given as

$$PSD_{ADSL,US}(f) = K_{ADSL,US}(f)\frac{\left[\sin\left(\frac{\pi f}{f_0}\right)\right]^2}{\left(\frac{\pi f}{f_0}\right)^2}, \qquad 0 < f \leq \infty \tag{4.1}$$

With f_0 the sampling the frequency and $K_{ADSL,US(f)}$, the total ADSL upstream transmitted power in *dBm/Hz*, and is given by

$$K_{ADSL,US}(f) = \begin{cases} -38dBm/Hz \\ -38 - 24\left(\frac{f - 138000}{43125}\right)dBm/Hz \end{cases}$$

[60] where f is the frequency in Hz. Integrating Equation 4.1 between zero and infinity with respect to f, gives the transmitted power in watts.

4.2.2 ADSL Down Stream PSD

Equation 4.2 shows the single sided transmit spectral density of a downstream ADSL signal [61].

$$PSD_{ADSL,DS}(f) = K_{ADSL,DS}(f)\frac{\left[\sin\left(\frac{\pi f}{f_0}\right)\right]^2}{\left(\frac{\pi f}{f_0}\right)^2}\left|LPF(f)\right|^2\left|HPF(f)\right|^2, \; 0 < f \leq \infty \tag{4.2}$$

Where the sampling frequency, $f_0 = 270kHz$; the total downstream-transmitted power before shaping filters, $K_{ADSL,DS} = 110.4mW$; the 3db cut-off frequency given by

$f_{3db} = 1.104MHz$, the low pass filter given by $|LPF(F)|^2 = \frac{1}{1+\left(\frac{f}{f3b}\right)^8}$, and the high pass filter given by $|HPF(f)|^2 = \frac{f^8}{f^8 + f_{3db}^8}$.

Figure 4.1 shows the PSD of both the upstream and downstream of ADSL.

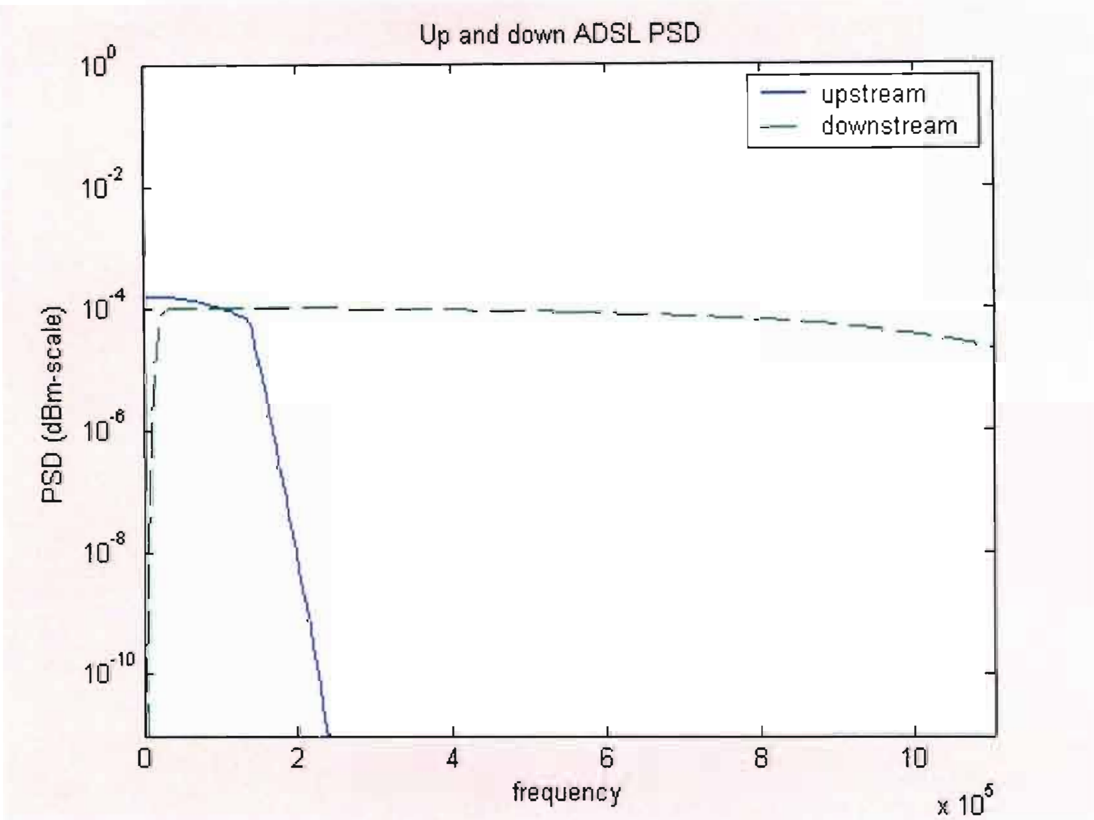

Figure 4.1: The power spectral density of ADSL for both upstream and down stream.

4.2.3 HDSL PSD

In Chapter 2 it has been mentioned that HDSL has the upstream bandwidth equal to the downstream bandwidth. The single sided transmit spectral density is given by

$$PSD_{HDSL}(f) = K_{HDSL}\frac{2}{f_0}\frac{\left[\sin\left(\frac{\pi f}{f_0}\right)\right]^2}{\left(\frac{\pi f}{f_0}\right)^2}\frac{1}{\left[1+\left(\frac{f}{f_{3db}}\right)^8\right]} \quad , 0 < f \leq \infty \qquad (4.3)$$

[62] where the sampling frequency, $f_0 = 392kHz$; $f_{3db} = 196KHz$; the total HDSL transmitted power, $K_{HDSL} = \frac{5}{9}\frac{V_P^2}{R}$; the line voltage, $V_P = 2.70Volts$, and the line resistance, $R = 135\Omega$.

4.2.4 ISDN

ISDN is the foundation of DSL technologies. Upgrading this technology to today's DSL technologies was because of some issues discussed in Chapter 2 that were not addressed in ISDN. Equation 4.4 shows the single sided transmit power spectral density of the ISDN signal.

$$PSD_{ISDN}(f) = K_{ISDN}\frac{2}{f_0}\frac{\left[\sin\left(\frac{\pi f}{f_0}\right)\right]^2}{\left(\frac{\pi f}{f_0}\right)^2}\frac{1}{\left[1+\left(\frac{f}{f_0}\right)^4\right]} \quad , 0 < f \leq \infty \qquad (4.4)$$

Where $f_0 = 80KHz$; the total ISDN transmitted power, $K_{ISDN} = \frac{5}{9}.\frac{V_P^2}{R}$; $Vp = 2.50Volts$ and $R = 135\Omega$

4.2.5 T1

T1 circuits occur less in today's existing wire-line network as they have been replaced by other new technologies. In the developing countries there is no evidence of their existence or a complete replacement of these circuits. The most used code for T1 is alternate mark inversion code (ATMI). Equation 4.5 shows the single sided power spectral density of the transmit signal.

$$PSD_{T1}(f) = \frac{V_P^2}{R_L}\frac{2}{f_0}\frac{\left[\sin\left(\frac{\pi f}{f_0}\right)\right]^2}{\left[\left(\frac{\pi f}{f_0}\right)\right]^2}\left[\sin\left(\frac{\pi f}{2f_0}\right)\right]^2 |H_{Shape}(f)|^2 |H_{Trans}(f)|^2,\ 0 < f \leq \infty \qquad (4.5)$$

Where

$$|H_{Shaping}(f)|^2 = \frac{1}{1+\left(\frac{f}{f_{3db}}\right)^6} \text{ and}$$

$$|H_{Transformer}(f)|^2 = \frac{f^2}{f^2 + f_{3db}^2}$$

$V_P = 3.6$, $R_L = 100\Omega$, $f_0 = 1.544 MHz$; the 3dB frequency of the third order Butterworth low pass shaping filter, f_{3dB} = 3.0 MHz

Figure 4.2 shows the PSDs of HDSL (136kb/s), HDSL (2048kb/s), ISDN and T1

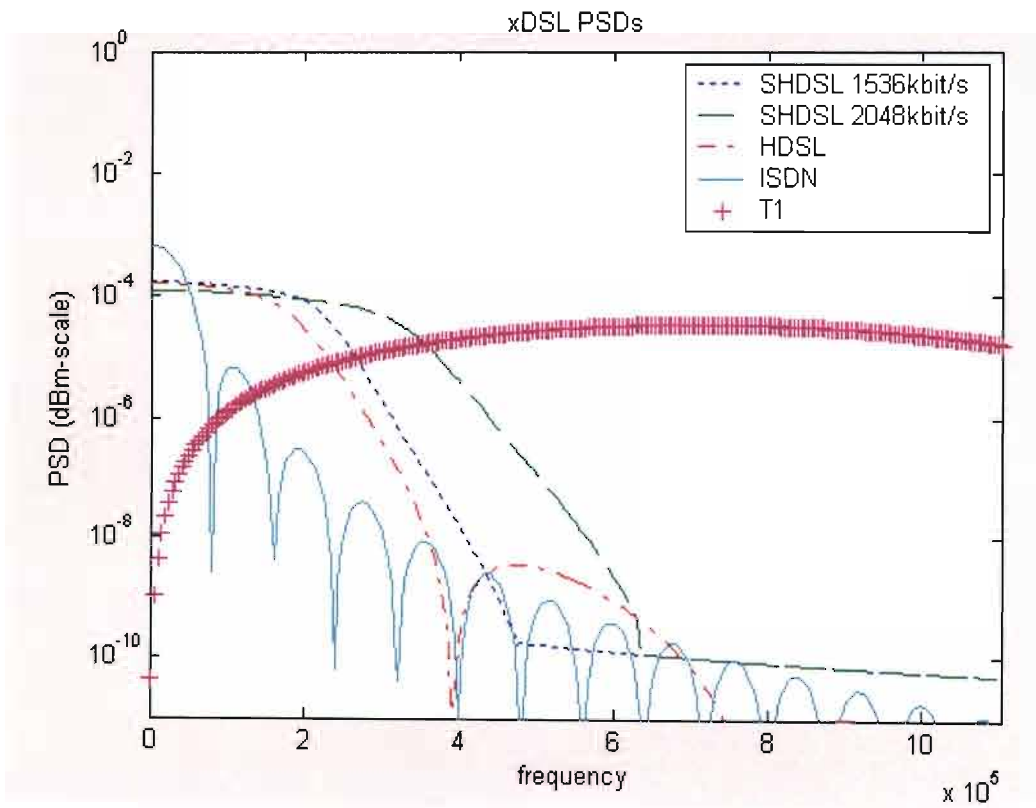

Figure 4.2: The power spectral densities of DSL symmetrical technologies

4.3 FEXT and Next Analysis

4.3.1 Next Analysis

At a given frequency only a few of other pairs may contribute significantly to crosstalk, but over all frequencies many lines contribute. The coupling is the one that is averaged over many pairs. The sum of many coupling functions is assumed constant and is given by

$$\sum_{n} |X_n(f)|^2 \approx k' \tag{4.6}$$

A single twisted pair binder has a coupling function given by

$$S_n(f) = k_{next} f^{1.5} \tag{4.7}$$

Where k_{next} is a constant given as

$$k_{next} = 10^{-13}\left(\frac{N}{N_{max}}\right)^6$$

N is the number of disturbers in the cable carrying the DSL services, N_{max}, the maximum number of disturbers in a cable, given by

$N_{max} = N_{binder-pairs} - 1$.

Therefore the PSD for a NEXT is given by

$$PSD_{NEXT}(f) = PSD_{disturber}(f).S_n(f) \tag{4.8}$$

For a 50 pair binder, $N_{max} = 50 - 1 = 49$

Therefore the NEXT equation for a 50 pair cable is given as

$$PSD_{NEXT}(f) = PSD_{disturber}(f).\left(\frac{N}{49}\right)^{0.6}.10^{-13}.f^{1.5} \tag{4.9}$$

where 10^{-13} is the coupling coefficient for 49 disturbers, with f being the frequency in Hz. It can be seen in this equation that crosstalk increases with an increase in frequency at $10\log f^{1.5}$= 15log (f), which is 15dB/decade increase with f. A disturber can be defined as any other existing system in the binder, which is affecting the performance of the service, delivered through a twisted pair(s) to the customer.

4.3.2 FEXT Analysis

The far end crosstalk power spectral density is given as

$$PSD_{FEXT}(f) = PSD_{disturber}|H(f)|^2\left(\frac{N}{49}\right)^{0.6} k_c df^2 \tag{4.10}$$

In this equation d is the coupling path distance in feet and k_c, the coupling factor. This factor is equal to 9×10^{-20} and sometimes given as 8×10^{-20}. This factor can vary from one pair combination to another. $PSD_{disturber}$ is the power spectral density of the interfering signal and N is the number of disturbers in a bundle, f, the frequency of the interfering signal in Hz, and $|H(f)|^2$, the channel insertion loss.

For d given in meters this equation can be written as: -

$$S_f(f) = k_c\left(\frac{N}{49}\right)^{0.6} f^2\left(\frac{d}{0.3048}\right)|H(f,d)|^2 S_2(f) \tag{4.11}$$

A simplified FEXT for a 50 pair binder cable can be approximated as

$$FEXT_{49} = k_c l f^2 \tag{4.12}$$

From the above equation it can be seen that the FEXT is dependent on the loop length and the frequency. FEXT increases with the increase in loop distance and frequency. Since FEXT increases with the square frequency (20dB/dec); that means FEXT is more sensitive to transmission frequencies. Figure 4.3 shows the NEXT xDSL PSDs with different number of disturbers.

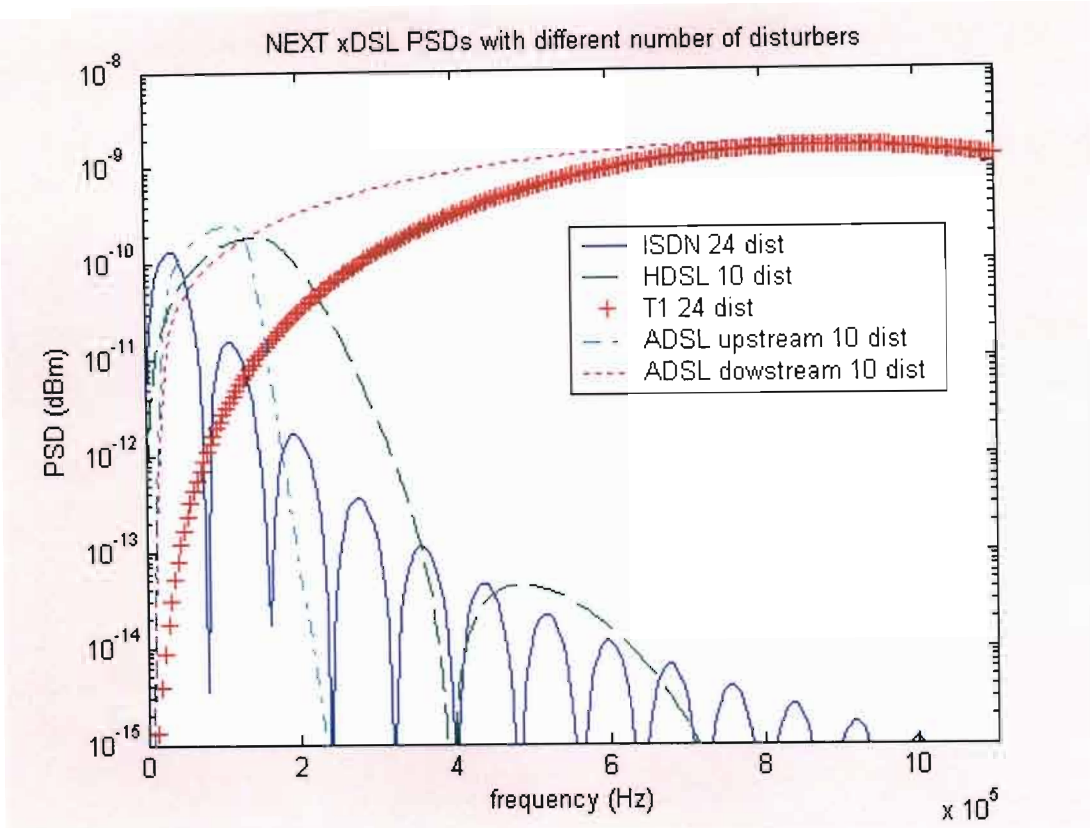

Figure 4.3. PSD of DSL varieties with NEXT for a given number of disturbers

4.4 Performance of DSL Technologies under Different Transmission Conditions

4.4.1 ISDN Performance

In chapter 2 ISDN has been defined as a technology that has better reach but limited bandwidth. ISDN uses 2B1Q code for transmission as described in Chapter 2. Like all other DSL technologies, ISDN performance depends on the number of disturbers in the operating environment. Equation 4.9 showed that the level of crosstalk depends on the number of disturbers in the loop plant. Figure 4.4 shows the performance of 160kb/s ISDN with 70dB echo canceller transceiver over a 26 AWG loop. The performance of ISDN with out crosstalk is dictated by the performance of the transceivers. Bundling 50 twisted pair of 26 AWG and transmitting over a single twisted pair, leaving the 49 pairs not transmitting, gives the maximum performance that is dictated only by the performance of echo canceller transceivers. With transceivers operating at a bit error rate (BER) of 10^{-7}, with a 6dB margin, the maximum achievable distance is 6.22km. Adding a single pair, which means transmitting over two pairs in the same binder, leaving the 48 pairs not transmitting, reduces the achievable distance to 6.01km. The distance decreases as the number of disturbers is increased in the binder. The worst case occurs where all the pairs in the binder are transmitting. Monitoring the performance of a single pair, taking others as disturbers gives a distance of 5.5km.

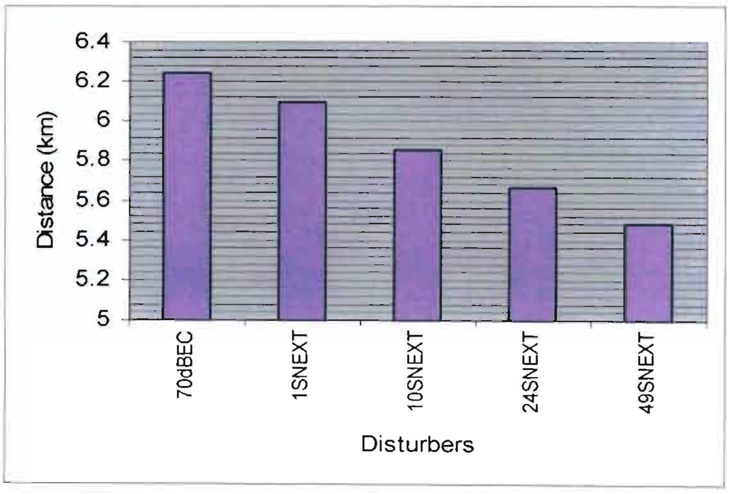

Figure 4.4: ISDN performance under self NEXT disturbers

This type of degradation of performance, where the system is disturbed by the presence of other systems of the same technology is called self-disturbance. The two types of self-disturbances are self near end crosstalk (SNEXT) and self far end crosstalk (SFEXT).

4.4.2 ISDN Performance with Other Systems

Figure 4.5 shows the performance of ISDN with other DSL systems, over the same 50 pair copper bundle. In this case the potential disturbers are HDSL, SDSL and RADSL. Consider a case of transmitting ISDN over a single pair, with the rest of 49 pairs transmitting CAP RADSL. It can be seen that ISDN performs better with RADSL reaching a maximum distance of 6.01 km. With the same number of disturbers of SDSL, the reach is reduced to 5.92 km, with HDSL disturbers making the worst case of 5.8 km.

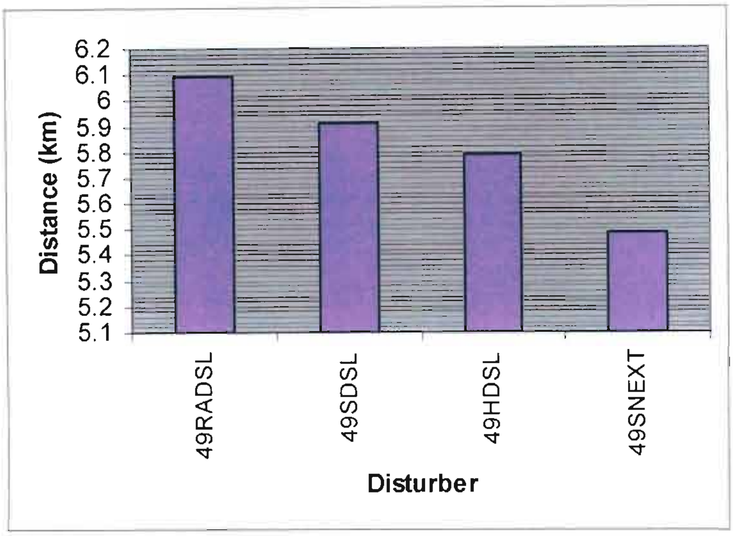

Figure 4.5: ISDN performance under various disturbers

ISDN has achieved a worst-case reach of 5.8km with these disturbers. The worse case on SNEXT was 5.5km. That means ISDN is more sensitive to other ISDN systems than other DSL systems. It can be concluded that bundling a high number of ISDN systems in the same binder group will shorten the reach. That implies that, where the reach is of great importance like in rural areas bundling together these systems must be avoided.

4.4.3 HDSL Performance

In chapter 2 HDSL has been defined as one of the early DSL technologies like ISDN. HDSL also uses 2B1Q code for transmission. Figure 4.6 shows the performance of 784kb/s HDSL, with 70dB echo canceller transceivers, 6dB margin and a BER of 10^{-7}. The transmission media is the same as in the above systems; the same 50 pair copper bundle is used. Like in ISDN the maximum performance is archived when there are no disturbers, with the reach being dictated by the performance of the echo cancellers. The maximum reach without disturbers is 3.9 km.

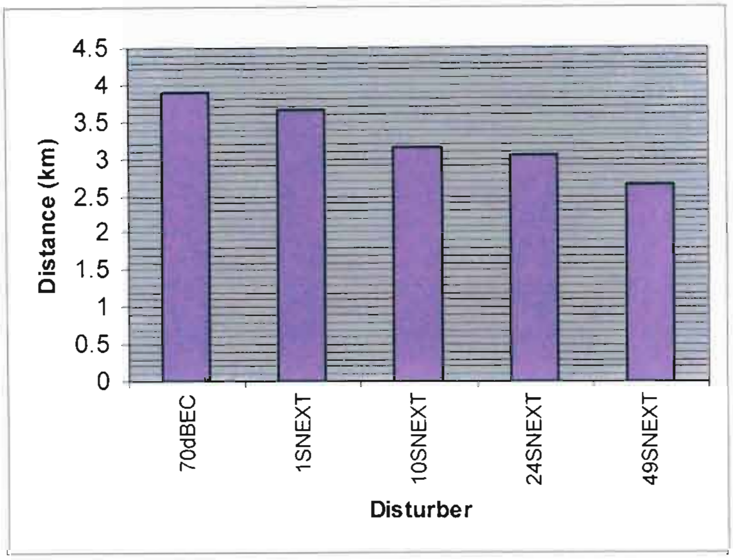

Figure 4.6: HDSL performance under self NEXT disturbers

The reach here also decreases with the increase in the number of disturbers. The worst case is when all 50 pairs are transmitting HDSL signals. Monitoring the performance of a single pair gives a reach of 2.9 km. The difference in reach between the worst case and the best performance is 1 km (3.9-2.9). For ISDN the self NEXT (SNEXT) difference was 0.7km (6.2-5.5). That shows that ISDN still performs better than HDSL on SNEXT. Which means rolling over HDSL system over the copper bundle will degrade the reach performance.

Like in the case of ISDN, the same applies to HDSL; the trade off between reach and a number of HDSL pairs in the binder must be used carefully when deploying DSL technologies.

4.4.4 HDSL Performance with Other Systems

Figure 4.7 shows the scenario of HDSL running with other systems in the same copper bundle. The other existing DSL systems are ISDN, RADSL, and SDSL. HDSL performs better with 49 disturbers of ISDN, with a reach of 3.7km. However, this reach is still less than the SNEXT reach of 4.2km that was achieved. The worst-case scenario is when HDSL is running with 49 SDSL disturbers, with a performance slightly better than the SNEXT worse case. That means SNEXT remains the greatest threat in HDSL systems.

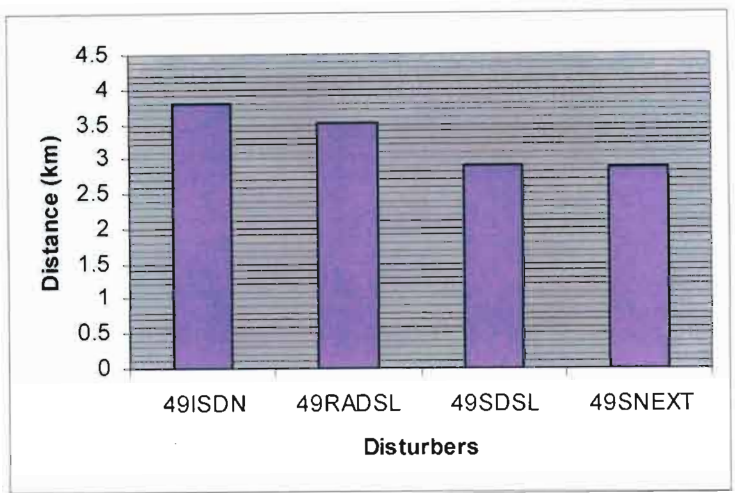

Figure 4.7 HDSL performance under different disturbers

4.4.5 SDSL Performance

SDSL as described in chapter 2, transmits at symmetrical rates in both up and down stream. 2B1Q is used as a transmission code. Figure 4.8 shows the performance of this technology over the same copper bundle described in the above technologies. Since this technology is transmitting at high bandwidths in both directions, SNEXT becomes the most degrading disturber. As the transmission rate is increased, the level of crosstalk also increases, thus shortening the reach. Equation 4.9 showed that NEXT is dependent on the transmission frequency.

With other technologies, e.g. ISDN as seen in Figure 4.9, the performance is good. But because of high bidirectional transmission bandwidth, this technology is capable of degrading others.

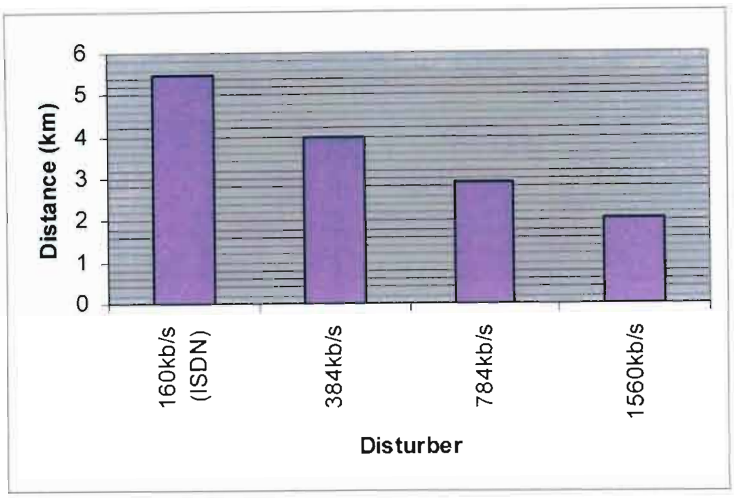

Figure 4.8: SDSL performance under various data rates self NEXT

It is there fore advisable to bundle a high number of SDSL lines with other services.

4.4.6 RADSL Performance

Rate adaptive digital subscriber line technology is a technology that delivers rates that change according to the loop conditions at that particular moment. If the loop conditions change while this system is on, the system adapts itself by changing the transmission rate. This technology uses carrierless amplitude (CAP) modulation for transmission. Consider a down stream rate of 680 kb/s RADSL system. Figure 4.9 shows the performance of this system in the presence of T1 AM1, HDSL, and ISDN.

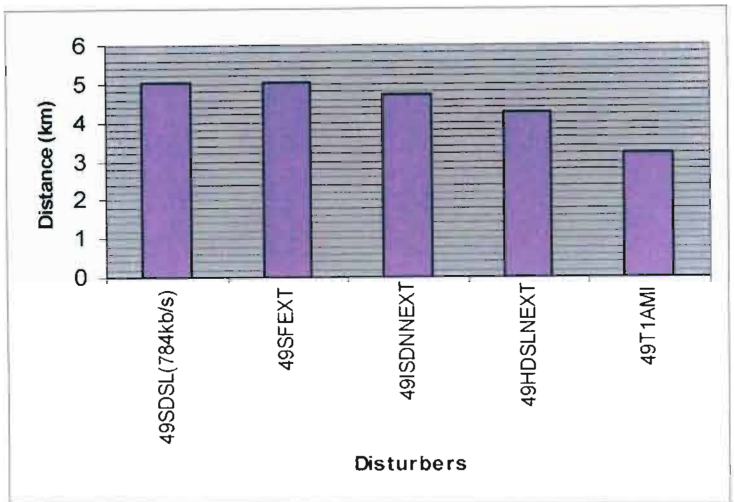

Figure 4.9: RADSL downstream performance under various disturbers

It can be seen that the down stream performance of RADSL is not affected by the far end crosstalk (FEXT) from the 49 self-disturbers. The case where the reach performance is badly degraded is when the rest of the lines are transmitting T1 AMI signals. Figure 4.10 shows the upstream performance. The upstream bandwidth has longer reach than downstream. This is because upstream does not suffer from high attenuations as it is transmitting at low frequencies. Unfortunately downstream bandwidth the most important as it is the one that delivers the service to the customer. That means the network has to be designed looking more on the downstream bandwidth, as it is the one that is quickly degraded.

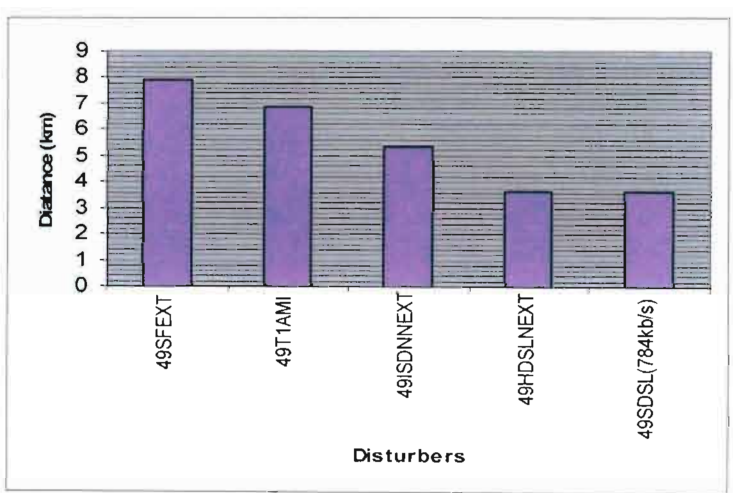

Figure 4.10: RADSL upstream performance under various disturbers

It can be concluded that it is possible to put a number of RADSL systems in the same bundle and achieve better reach. This is a unique and a very useful feature and it addresses both the question of reach and high subscriber density.

4.4.7 ADSL Performance

ADSL is a technology that transmits in asymmetrical rates, up and down stream. This technology uses DMT code for transmission. Consider an ADSL transmitting at 272kb/s downstream. Figure 4.11 shows the upstream performance of this technology, in the presence of 49 ADSL disturbers, 49 ISDN, 49 HDSL and 49 SDSL.

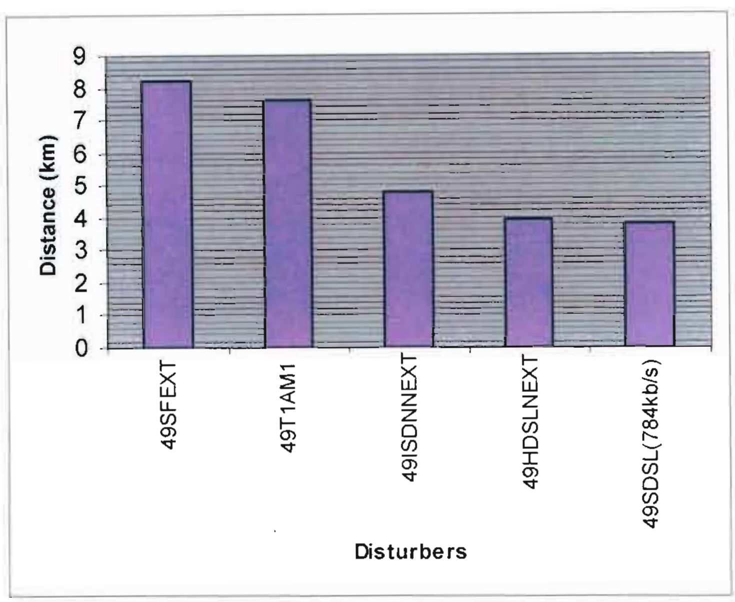

Figure 4.11: ADSL upstream performance under various disturbers

ADSL upstream seems not to be affected by far end crosstalk, from the 49 ADSL disturbers. T1 AM1 is also not degrading the reach performance as badly as it was in RADSL. The only threat for this technology is SDSL. SDSL degrades ADSL reach performance from 8.2km to 3.8 km. Increasing the data rate of SDSL results in more reach degradation. The reason is that SDSL transmits at high rates in both directions. Figure 4.13 shows the down stream performance, transmitting at 680 kb/s.

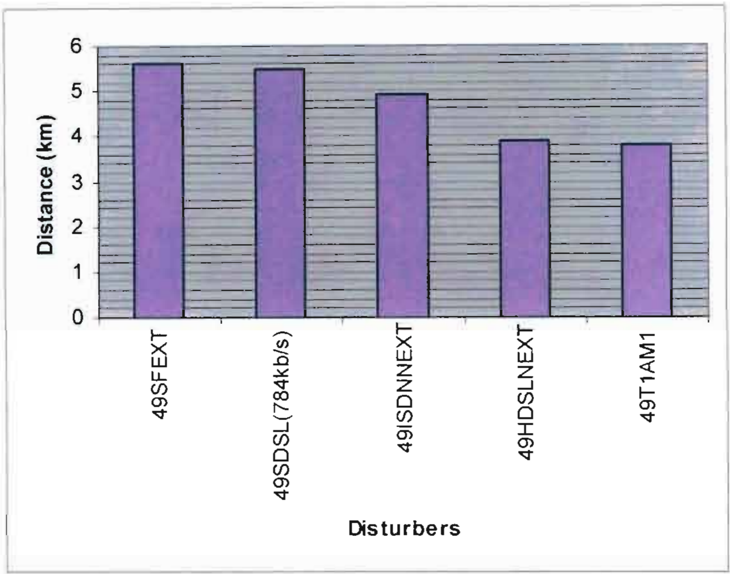

Figure 4.12: ADSL down stream performance with various disturbers

It can be seen that upstream reaches far longer distances than downstream. The worst case for downstream is the 49 T1 AM1 disturbers. The reach here is 3.8 km, which is the same as the reach of the upstream with 49 SDSL disturbers.
This shows that when deploying ADSL, bundles with SDSL should be avoided in order to achieve better reach performance.

4.4.8 VDSL Performance

VDSL is a very high data rate wire-line technology. Because of extreme high transmission bandwidths, VDSL can potentially displace existing services in the network. VDSL is also facing a challenge of electromagnetic compatibility with radio broadcasters.

4.5 Conclusion

Spectral compatibility is an important aspect of DSL network design. Spectral compatibility determines if the DSL system will work well or not. In this chapter it has been shown that a proper selection of technologies running in the same bundle is of great necessity.

The spectral compatibility between services is sometimes determined by the type of line code used. The level of overlapping of PSD determines the level of compatibility between the signals. If the signals of the same power spectral density are transmitted towards the same direction, that results in far end crosstalk (FEXT), which is not that degrading. Transmitting signals in the opposite direction results in near end crosstalk (NEXT). Echo cancelled support systems are only exposed to self near end crosstalk (SNEXT), while DMT and CAP systems are exposed to self far end crosstalk (SFEXT) and NEXT from other systems.

Spectral compatibility has led to a solution of unbundling the local loop by most of the DSL telecommunications companies.

Spectral compatibility becomes even more sensitive in the urban environment where there are concentrated subscribers. In such scenarios it more likely to have a high number of copper pairs in a single binder group.

Adequate spectral compatibility appears to be a trade off between reach, data rate and the number of DSL subscribers.

In a rural scenario, managing the spectrum in DSL systems is easy, since the subscribers are scattered leading to very few pairs in a bundle. The challenge however is to deploy services with maximum reach.

Chapter 5

DSL Solutions and Cost Parameters

5.1 Introduction

It has been shown in Chapter 3 that the transmission of high frequencies over copper transmission lines results in high attenuation. This was demonstrated in Equation 3.13 where α , the attenuation constant is directly proportional to f, the transmitted frequency. In Chapter 4, it has been shown that the PSD of the crosstalk depends on the number of disturbers in a network. It has also been shown that the reach also depends on the level of the PSD of interferers. FEXT has been identified as the crosstalk that depends on the loop length. In Chapter 1 it has been mentioned that developing countries have a higher percentage of long loops than developed countries. This is because of the high number of remote residents compared to the urban residents.

This leads us to the conclusion that developing countries consist of two different types of subscribers, subscribers that can be served using only the existing copper plant, and the remote subscribers who need further long reach solutions.

This section investigates and proposes the DSL deployment entry points, sequences, and technologies suitable for the subscriber patterns described in Chapter 1. These patterns represent most of the expected residential and business settlements found in developing countries. This is done in order to narrow down the study for the purpose of analysis. It is assumed that any of the residential patterns, from suburban to rural environment, should fit one of the described patterns.

The performance of the deployed technologies is analysed using FTW Full Service Network (FSAN) and MATLAB software.

Simulations Objectives:-

- The recommended technology in a particular area should meet the required bandwidth for the particular technology
- The recommended technology should be within the standardised transmission range
- The recommended technology should not degrade the already existing services
- The deployed technology should allow future network upgrades.

Simulation Parameters:-

- All simulations include a standard AWG noise channel of -140dB/Hz
- Transmission lines of 24 AWG are used in order to achieve less attenuation
- PSDs with less impact on ADSL, SDSL, SHDSL, and VDSL, with a maximum distance of 4km have been selected
- A coding gain for SHDSL is 5dB with a noise margin of 6dB

5.2 Deployment Strategy

One of the strategies that have proven to be feasible for providing telecommunications services accessibility in the developing countries is the deployment of both coin and card public telephones. This strategy has benefited even the very financial disabled, who cannot afford the fixed telephone lines and mobile phones.

The same strategy has to be adopted in the deployment of DSL, with the reason being that facilities required for accessing services like Internet are even more expensive. Out of the 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. A number of rural residents have never seen a computer before.

The best entry point for the introduction of these services to rural residents is the deployment of these services in the telecentres. These telecenters can be placed so that residents do not walk unacceptably long distances to get access. A distance of 1.5km is a reasonable distance, with this distance decreasing in the future.

Provisioning of these services in telecenters 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 teacher 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. Figure 5.1 shows the traditional service deployment sequence that has been used for years by most of the telecommunications companies.

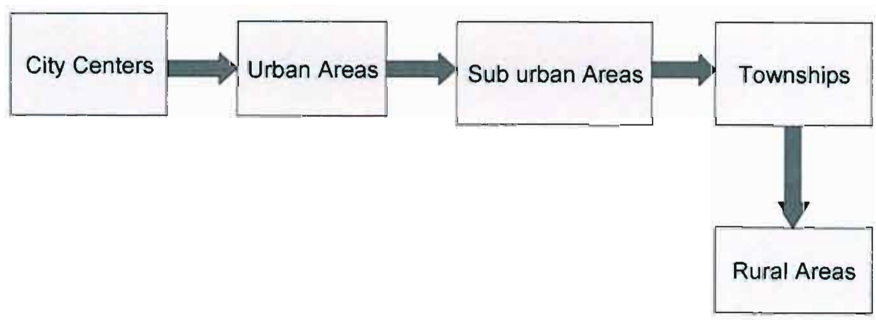

Figure 5.1: Traditional Service Deployment sequence

It is this sequence that has resulted in uneven distribution of services in most of the countries. It takes years to reach the rural areas, to a point of not reaching most of the remote areas. This sequence is based on business interests than development. The proposed sequence that bridges the digital divide is as shown in Figure 5.2.

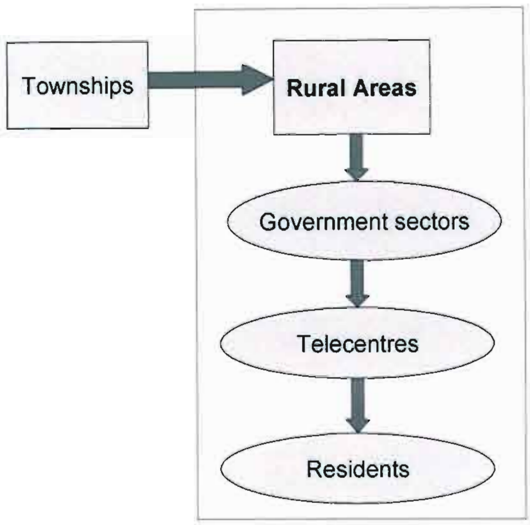

Figure 5.2 : Proposed DSL Deployment sequence

The proposed sequence favours the business interests, thus attracting the investors but also bridging the divide between the already developed areas and the underdeveloped areas. Government sectors include schools, hospitals, clinics, agricultural sectors, etc.

5.3 Techniques and Service Rollout

Responses to customer service requests must be as fast as possible. Putting the requests on long queues should be avoided as it might lead to the loss of interest by the customers. The two technological solutions that are used here are copper and a combination of copper and fibre.

5.4 Proposed Services for Rural Residents

Rural subscribers will hardly need high bandwidth applications, which demand more than high speed Internet. This will take some time to happen. Very high bandwidth services are often required by educated and business people. As the level of skills and knowledge improves, rural residents will slowly need such applications.

The services proposed for deployment in rural areas for now are high speed internet for residential subscribers, a combination of high speed internet, very high bandwidth applications like Video conferencing and other multimedia services for telecenters, government sectors, schools and businesses.

5.5 Distribution of Subscribers around the Central Office

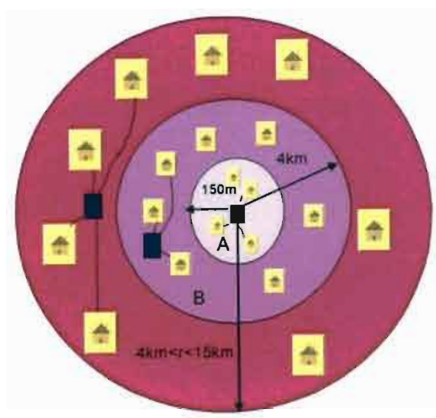

Figure 5.3: Loop Distribution from the CO

Figure 5.3 shows the distribution of subscribers around the central office. It can bee seen that there are subscribers that are within a distance of 150m from the central office (Zone A), subscribers within a distance 150m ≤ 4km (Zone B), and subscribers at distance greater than 4km<15km (Zone C). As the distance increases away from the central office, the subscriber density decreases.

5.5.1 Zone A

Subscribers in zone A are more likely to be a combination of small businesses and residents. Because of the nature of these customers, this zone is regarded as a high bandwidth zone. The residents here are connected directly to the central office. Within this zone all DSL technologies are possible. In this region VDSL is recommended for large businesses and the telecentre. This is because VDSL can deliver up to 26Mb/s of symmetrical rates over this distance. VDSL will also give a bonus of copper savings as it can support both DSL and voice signals over the same copper pair.

It has been mentioned in Chapter 2 that SHDSL requires a separate line as it cannot support simultaneous access of voice and data over the same line. SHDSL is recommended in this region for low bandwidth symmetrical applications. Figure 2.11 shows the ADSL2 performance. This technology can deliver between 20 and 25 Mbps at a distance of 2km. This technology can also perform very well in telecenters, schools and businesses at this zone. Since ADSL can support both voice and data on the same line with the additional advantage of asymmetrical data transmissions, which is always the requirement for the residential applications, this technology is recommended for the residential subscribers. Figure 5.4 shows the possible ADSL and SHDSL speeds that can be delivered within the range of 4km without disturbers.

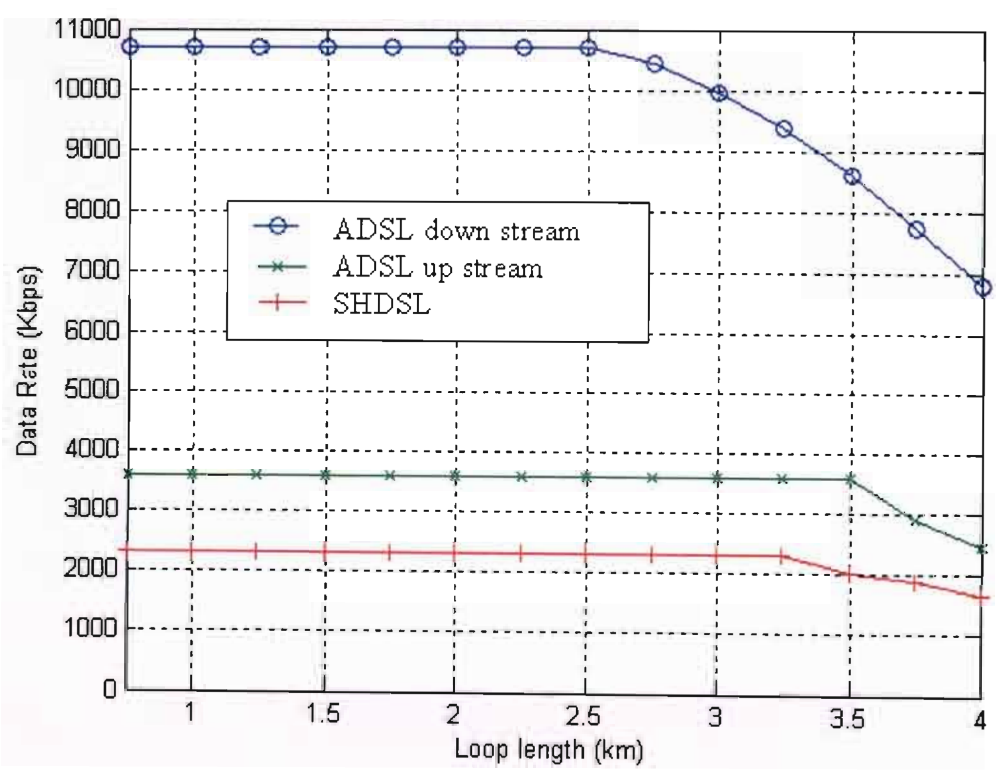

Figure 5.4: ADSL and SHDSL unbundled copper pairs performance

At a distance less than or equal to 2.5 km, ADSL can deliver speeds of about 10.75 Mbps downstream, and 3.6Mbps upstream, with SHDSL delivering 2.25 Mbps. Looking at Table 2.3, both the residential and business applications are possible with these bandwidths. It is unfortunate that zone *A* can only cover approximately 20% of the households in the developing countries. In the European countries a distance of 150m from the central office covers 39% of the households [40].

5.5.2 Zone B

At this zone, subscribers receive services through the bundled copper cables that run from the central office to the distribution point. In Chapter 4, it has been mentioned that bundled copper pairs require spectral management. In order to ensure proper functioning and dimensioning of the network, a bundle should not carry more than 50 pairs.

It has been mentioned in Chapter 2 that ADSL and RADSL allow asymmetrical transmissions, and simultaneous use of a single pair for both data and voice. Because of that reason, the recommended services for subscribers within this region are ADSL and RADSL for residential subscribers and SHDSL for telecenters and small businesses. RADSL will be provisioned to subscribers who cannot afford fixed ADSL data rates. Since RADSL can tolerate loop impairments and can function without sophisticated and expensive loop tests, it makes it affordable to these subscribers. The data rates delivered to these subscribers will depend on the loop conditions, but as per agreement with the service provider, the rates must be reasonable, and customers must be guaranteed a certain level of quality of service. Figure 5.5 shows the possible network performance for SHDSL subscribers in this region. The drop wire is assumed to be 24 AWG.

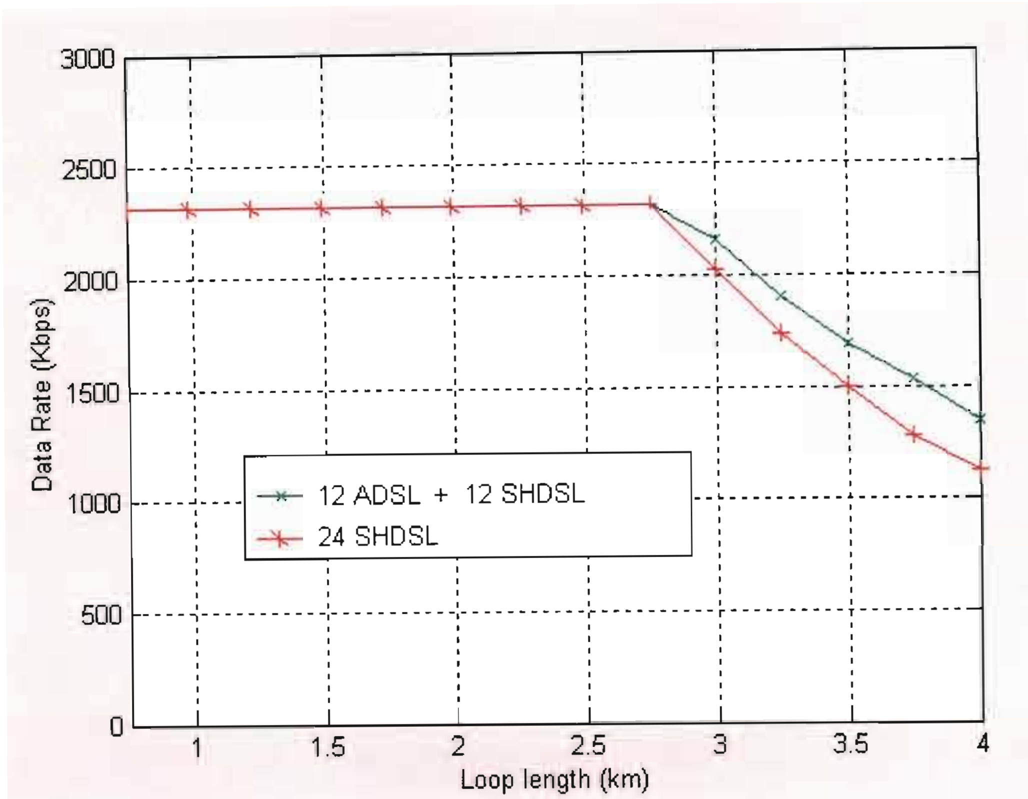

Figure 5.5 SDHDSL performance, telecenter and business subscribers

SHDSL delivers a data rate of 2.3Mbps up to a distance of 2.75km. After a distance of 2.75km, the disturbers start degrading the data rate, with 24 SHDSL making the worst case, and a mixture of 12ADSL and 12 SHDSL achieving the better performance. That means subscribers at a distance of 4km can receive data rates of approximately 1.25Mbps. In Chapter 4 it has been mentioned that bundling 50 RADSL pairs in a single binder does not affect the RADSL performance badly (see Figure 4.10). SHDSL is also spectrally compatible with RADSL (see Figure 4.8). The worse impairment namely T1, is not expected to be found in most of the rural areas. The best thing to do here is to have a separate bundle of RADSL systems consisting of a maximum of 50 pairs, and a separate bundle of SHDSL and ADSL with a maximum of 50 pairs combined. The binders can then be separated so as to avoid other interference from the neighbour binder. It must be noted that business subscribers expected in this region are fewer than those in zone A. Since SHDSL is recommended for business applications, which implies 24 SHDSL will be a rare scenario in this area. This area can cover up to 50% of the subscribers in developing countries.

5.5.3 Zone C

This area also requires spectral management. Because of long loops, this zone requires the combination of both fibre and copper cables. The longer the loops, the higher the level of disturbers. RADSL and HDSL are recommended for this region. These technologies have better performance on long lines. Teledensity is lower in this zone than in zone A and B, which means less copper pairs per bundle. Consider a scenario where there are 12 ADSL residential subscribers and 12 business and telecenter subscribers, receiving a data rate of 2.304 Mbps. Figure 5.6 and Figure 5.7 show the expected ADSL upstream and down stream performance respectively.

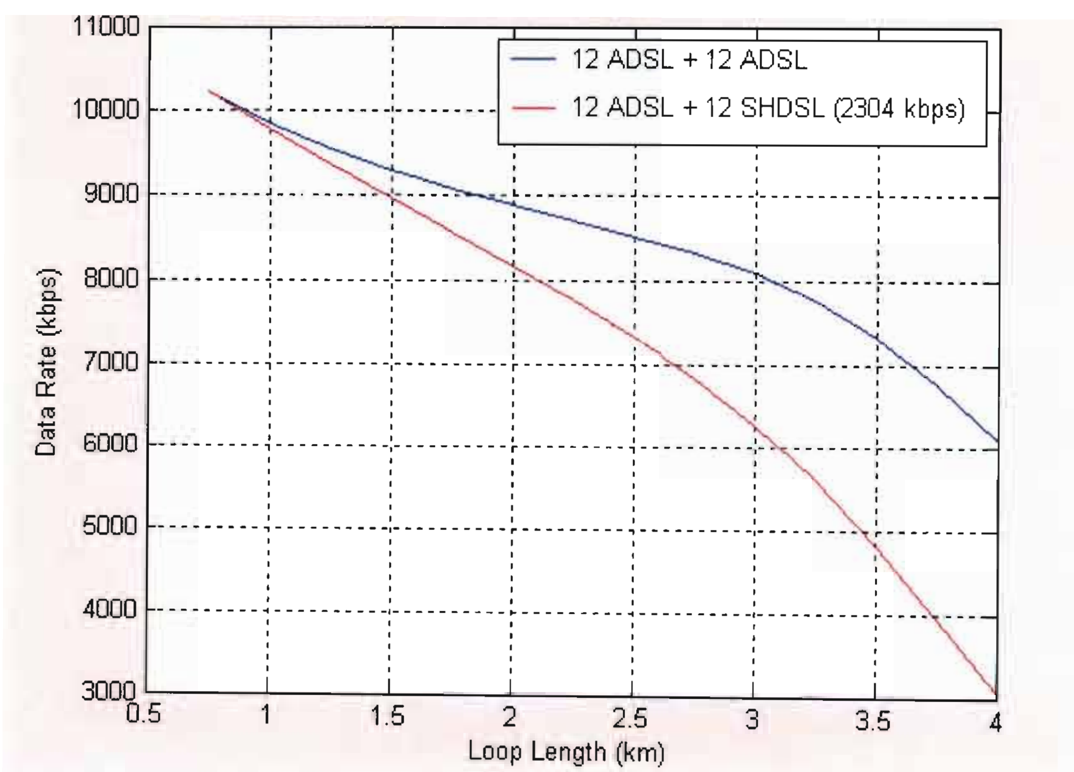

Figure 5.6: ADSL downstream Performance

It is now clear that a performance of 12 ADSL subscriber network with 12 ADSL disturbers remains better than the combination of ADSL and SHDSL. Although that is the case, a symmetrical data rate of 3Mbps remains reasonable enough for these subscribers. The residential applications in this area do not require very high bandwidth.

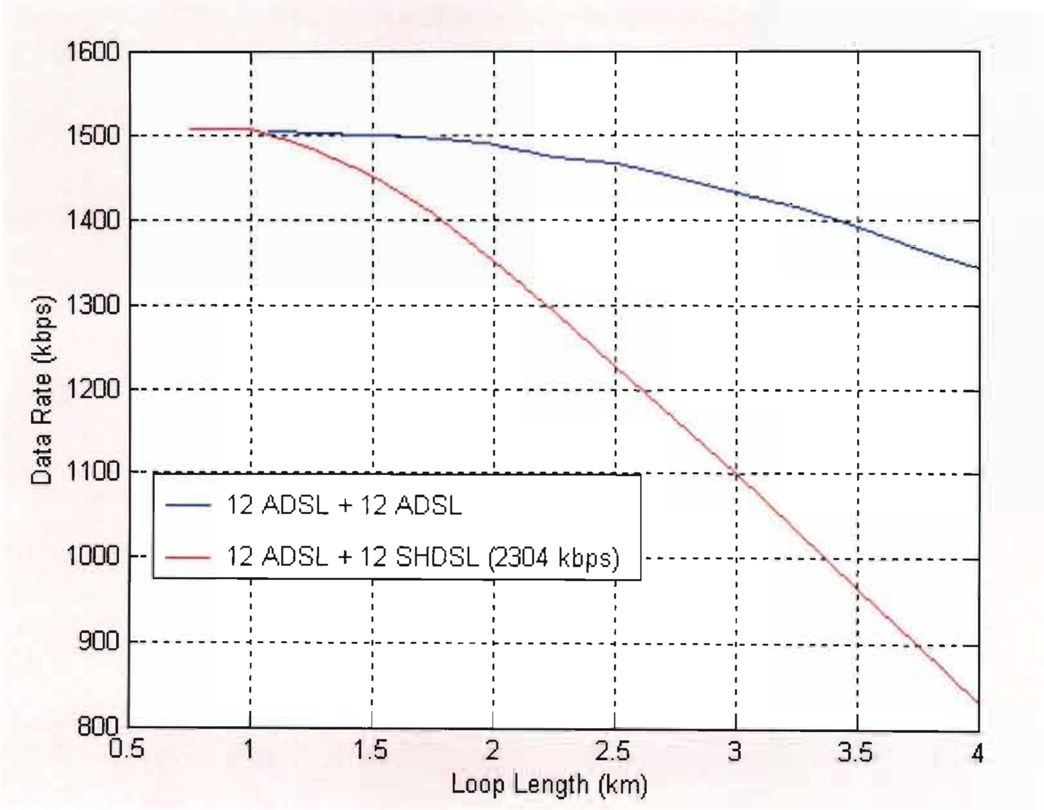

Figure 5.7: ADSL upstream performance

Upstream is heavily degraded from 3.6Mbps to 800kb/s by the combination of these different services. The best thing to do here is to unbundle the ADSL and SHDSL. This area can cover 30 % of the residents in the developing countries, with the reason being that in these areas there is less deployed wire-line infrastructure. Since zone C extends to 15km, this leads to the issue of long reach solutions.

5.6 Long Reach Solutions

Long reach solutions are there to connect subscriber located at a distance of up to 15km. The proposed solution combines both copper and optical fibre.

5.6.1 FTT area- The Solution to Sparsely Distributed and Clustered Residents

The sparsely distributed residential pattern has been identified as the pattern that is not easy to deal with in Chapter 1. Such patterns are found in the remote rural areas and farms. This pattern is characterised by low population density. That means there are only a few subscribers served by each central office. This pattern can cover approximately 55% of the subscribers in the developing countries.

5.6.2 Proposed Network

Figure 5.8 shows the proposed network for this pattern. In Chapter 3 it has been mentioned that distances between the subscribers and the central office are governed by the network design rules and principles. Since most of the subscribers here are located at a maximum distance of 11 km from the central office, a single fibre link is used for backhauling, thus bringing customers closer to the central office. Signals are multiplexed and transmitted to the optical network unit (ONU)/ hub, which serves a few subscribers located in that particular area. At the ONU, a splitter is used to separate these signals with a split ratio between 2 and 32 users. ONU may be placed at a distance of 9.5 km from the central office and the remaining connection is copper.

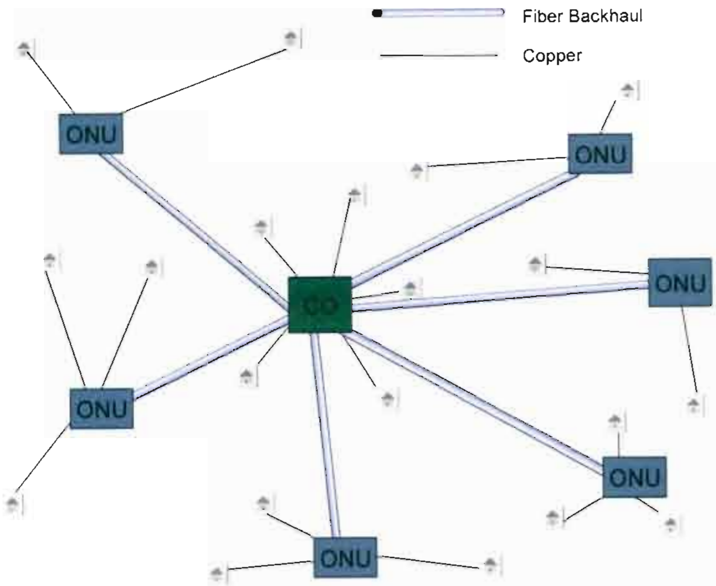

Figure 5.8: Sprucely distributed subscriber network

This pattern is found in zone C of Figure 5.3, starting just above 5.5km.

5.6.3 Fibre to the Building (FTTB) - Very High Bandwidth Solution

Here a fibre is rolled to the building. This is more suitable for large buildings like malls, tertiary institutions and other large buildings. This is obviously not for residential purposes, but only a business solution. For residential subscribers, FTTH remains a dream that will take time to be accomplished even in the developed countries.

5.7 Clustered Pattern Solution

This pattern results from residents residing in clusters in order to get closer to services, like schools, hospitals, clinics and other resources.

5.7.1 Proposed Network

Figure 5.9 shows the network proposed for these residents.

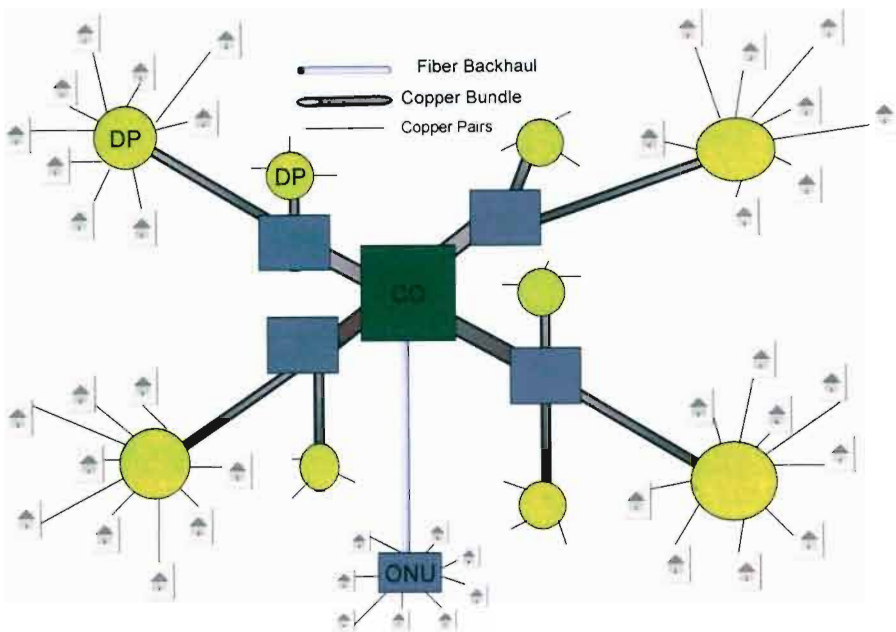

Figure 5.9: Cluster Pattern Subscriber Network

A copper bundle runs from the CO to the distribution point where a number of subscribers are being serviced. The advantage of these clusters is that they make it easy to dimension the network, and approximate network cost. This is very difficult in a sparsely distributed pattern. This pattern can be found in any zone of Figure 5.3. It can be seen that even in this pattern, subscribers located at a distance greater that 5.5km are brought closer using fibre backhaul.

5.8 Fibre to the Cabinet (FTT cab) - a Solution to Belt Pattern Residents

This pattern results from residents residing along the roads, riverbanks, and mountainous areas.

5.8.1 Proposed Network

Figure 5.10 shows the network proposed for this pattern.

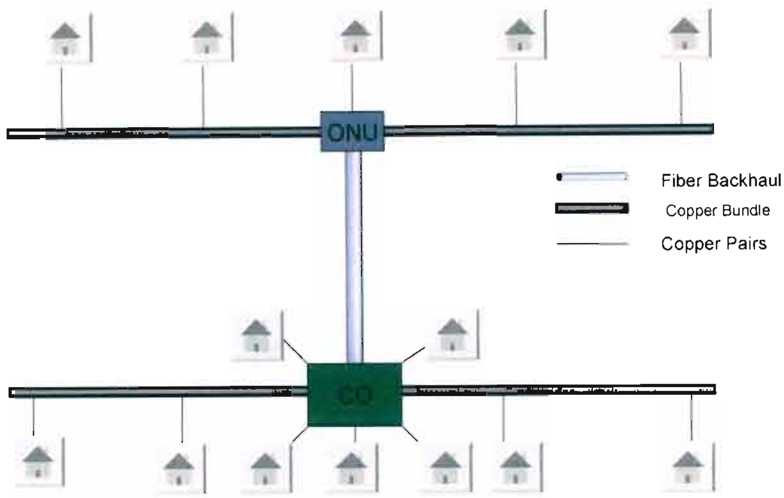

Figure 5.10 : Shelter Belt Subscriber Network

Subscribers located closer to the CO are connected directly with unbundled copper pairs. These subscribers have all the benefits of subscribers located at zone *A* in Figure 5.3

The bundled copper pairs are extended along the belt patterned homes, with a number of wires reducing in bundle, as they are dropped at homes. This bundle can run up to a maximum of 5.5km. For Subscribers located further than that, either across a river or road, a fibre is used for backhauling. This pattern can be found in any zone, but mostly at zone *A* and *B* in Figure 5.3.

5.9 Other Methods of Extending DSL reach

ADSL was initially designed for customers within a range of 5.49km from the central office. Due to the increase in demand and the pressure from the customers residing outside this range, further researches had to be done. This resulted in the investigation of methods, coming up with long reach DSL solutions. There are two solutions to the extension of a reach in xDSL systems

1. Use of ADSL mid-span repeaters
2. Increasing the transmitted power
3. Line Bonding

These three techniques have got their own advantages and disadvantages.

5.9.1 Mid-Span Repeaters

A repeater with a gain equivalent to the attenuated signal is placed at the middle of the line between the transmitter and the receiver. The disadvantage of this method is that the other signals at the same bundle at this point are weak, and therefore they can be corrupted very easily by a strong signal. This makes it difficult to use this method.

5.9.2 Paradyne Reach and Symetricon's Go-long Technology

Paradyne reach DSL guarantees 256 bit/sec DSL speeds up to a range of 5.5km [35]. Symmetricon's product called the Go-Long loop Extender is a repeater that is installed at the middle of the loop between the subscriber and the Central Office. The field trial conducted by Chester Telephone and independent provider in California found that Go-long could deliver more than 3Mb/s downstream and 406Kbit/sec upstream over 7.3km loop. Without Go-long the same loop could only support 96k bit/sec down stream. This is a viable solution for customers requiring applications that include high-speed Internet, telemedicine/video and business applications. The proposed DSL technology in this scenario is ADSL, for Internet applications. ADSL is recommended because this technology delivers asymmetrical bandwidth. It has been stated earlier that residents customers need more downstream bandwidth and less upstream bandwidth. A single repeater costs approximately $300 to $700.

5.9.3 Increasing the Transmitted Power

After travelling a long distance signals lose power. Because of this increasing transmit power will make attenuations less effective. The problem with this kind of method is the level of increase in crosstalk. This type of transmission suffers from increased Near End Crosstalk (NEXT). Equation 4.9 shows that increasing the power spectral density of the transmitted signal increases the power spectral density of the NEXT. Very strong signals will interfere with the other systems.

5.9.4 Symmetrical Digital Subscriber Line (SDSL) as a Long Reach Solution

Based on lab trails and a number of successful deployments, SDSL has become the most viable solution for providing services to business subscribers and the customers located outside the 6km range. SDSL allows the transmission of different symmetrical data rates. It is the best technology that has a better tolerance of loop impairment. The basic methods of increasing the SDSL reach include increasing the number of SHDSL links to a customer or by using a repeater. Use of more number of pairs can increase the bandwidth by up to four times [36]. The four-wire SHDSL can deliver a bandwidth of up to 4.6MBps, and it's one of the cheapest long reach solutions. IMA uses ATM standard for bonding up to 4 SHDSL pairs, resulting in bandwidth that is four times the bandwidth that is offered by 2-wire system for any given distance. The disadvantage of the four-wire implementation is that if one of the links drops all service is lost. The advantage of IMA against 4-wire is that even if one of the links drops, as long as there is one operating link the service will continue. This technology can also be used with one to four SHDSL pair, which gives a customer started with a single pair SHDSL an opportunity for up-grading the service without adding any new CPE hardware.

5.9.5 Repeating SDSL

Repeated SDSL has proven itself to be the viable solution for those customers located at loops greater than 12km.According to ITU-TG.991.2 SDSL can be repeated by up to 8 repeaters in series for reach extension [36]. This would allow a transmission of 1.5Mbps at a distance of 27.4km.The process of repeating SDSL is about regenerating the SDSL signals at equal intervals instead of just amplifying them. In this process all the noise generated is filtered out and the signal integrity and throughput levels are maintained. Both two pair and four pair SDSL can be repeated. This technology is recommended for remote subscribers who do not have the existing infrastructures. New long loops can be deployed without considering the normal voice loop design standards. There is no need for considering these standards, since SDSL cannot share the same line with voice services

5.10 Network Costs

Connecting subscribers located at a range less than or equal to 5.5 km is the cheapest network. This network requires only copper loops, which means there are no costly network upgrades required.

Sparsely distributed subscribers are the most expensive to cover with DSL technology. Fibre tends to be the most expensive part of the overall network. The fibre deployment costs vary due to the differences in geographical features in rural areas. Trenching required for fibre demands high labour and is also time consuming. Fibre costs also depend on the type of fibre, since some can only be buried and some aerial. Aerial can also be expensive as it requires poles for mounting which also demands high labour.

The advantage of fibre backhauled network is robustness and reduced maintenance costs. Unlike copper, which requires maintenance in every seven years, fibre does not require frequent maintenance. That means it is only the initial investments that are costly, but on a long run, this network becomes cost effective. The frequent and expected reduction in fibre costs brings even more hope in implementing networks of this kind.

The approximate ADSL implementation costs per line may start from R4, 000 to R5, 000 increasing with service speeds, with FTTC costs varying between R7, 000 and R7, 500 per line. Table 5.1 shows the parameters that determine the network costs.

Table 5.1: Network Costs parameters

DSL component	DSL cost parameter
DSLAM	Capacity (low port for rural application), installation and maintenance
Copper	Loop test, repair, installation in some areas, and maintenance
Fibre backhaul	Installation and maintenance
ONU	Installation and maintenance
POTS splitter	Installation and maintenance
Collocation cage	Installation and maintenance

5.11 Future Network Upgrades

It is obvious that as the time goes on, the increase in the number of literate and business people in rural areas, an increase of rural development projects, an increase in number of tourists to these areas, will obviously result in increase in bandwidth demand in the rural areas. With DSL this is not going to be the problem as long as the proper spectrum management is always maintained. Most of the developed countries with high bandwidth demand, have found unbundling the local loops as the best solution to better performance of DSL services.

5.12 Conclusion

Although the xDSL penetration is so much less in the developing countries compared to the developed countries, this gap can be closed as the advanced engineering techniques are being investigated and deployed. Developing countries are more challenging than the developed countries due to the high percentage of areas which are rural. Long reach DSL solutions are the hope of xDSL provisioning in the rural environment. Introduction of telecenters in the underdeveloped areas has got a great contribution in bridging the digital divide. Some people claim that there are some technologies that can be deployed from scratch and remain cheaper than DSL, which uses the existing telecommunications infrastructure. A comparative study can be done in order to investigate and identify the possible technologies of that nature. This would also help on covering those customers who are not connected with copper.

Chapter 6

Conclusion and Recommendations

6.1 Conclusion

It can be seen from the whole study that Deploying DSL in high concentrated areas is mostly cost effective and less challenging. The reason is that a single DSLAM serves a number of customers, thus bringing high revenues with fewer resources.

In the low population density areas, central offices were brought as close to the subscribers as possible, using the optical backbone. With this technology a single remote unit serves a number of customers, between 1 and 10 in a micro village, between 10 and 30 in a middle village, and between 30 and 50 in large villages. These technologies have proven to be more expensive but recover the capital costs in the long run. Most of the telecommunications companies (including the ones in the developed countries) are still hesitating to implement these long reach solutions. A few companies have tried in the European countries, and have proven these technologies to be cost effective. The deployment method used by the developed countries involves starting at the COs that serve a number of people, regardless of the location of the central office. Some start by doing a study on the incomes per home that needs DSL connection. Most of the companies have found that concentrating only on the number of subscribers is more accurate, because it is more likely to find that crowded central offices have affording subscribers.

In developing countries, DSL deployment will depend more on the current state of telecommunications infrastructure, usage of infrastructure, current and future demographics, economic costs and the understanding of benefits and need for expanding the infrastructure and services. The deployment here will be based more on improving people's lives. This means that the residential interests will need to be made first priority. Government has power of influencing businesses to invest in these technologies.

Subsidising such projects by government can be an effective catalyst in achieving this goal. South African government and other African countries have already demonstrated interest towards this goal, through the development of policies 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.

DSL deployments costs can be summarized as costs of existing network infrastructure upgrade and operational-maintenance costs.

6.2 Achievements

Based on the results of the performance of the recommended technologies, all subscribers connected with copper can now benefit from broadband services. The delivered bandwidth and reach are within the standard range. Each subscriber has a dedicated line which is not shared with any other user. Schools can now have fast and cost effective on-ramp to the information superhighway with affordable subscriptions. This improves the performance in schools as both the teachers and students have access to the world and real-time information.

Subscribers up to a maximum range of 15km are connected. Technologies have been deployed looking at the standard bandwidth and reach requirements.

Fibre to the cabinet is the solution to the remote subscribers located at the range between 5.5 and 15km from the central office. Complications associated with fibre installation include, high labour from civil works, requesting rights of ways to cross public roads and some other private properties. These might contribute to long term deliveries.

The high bandwidth feature, security, low maintenance costs, and robustness of this technology make it ideal for rural subscribers. Subscribers who do not have an existing copper infrusture can be connected using SDSL with repeaters. This technology can allow the deployment of new copper loops which are longer than those previously designed for voice services. DSL costs vary with the number of subscribers in a particular area. The lower the number of subscribers, the higher the cost of deploying. The cost of deploying DSL in a micro village of 1 to 10 users located at a distance of 5km, approximately doubles the cost of deploying DSL in an urban area. Increasing this distance to 15km will increase the costs to three times because of the required fibre backhaul.

At the end of the day there is no one-fit-all solution, but different solutions can be selected depending on the region's geography, population density, existing network infrastructure and deployment schedule constraints.

Residences, schools, businesses and government sectors can now have access to broadband services like distance education, telemedicine, video-on-demand, movie on demand, video conferencing and other multimedia services. This means great achievement in the improving the quality of life in the developing countries.

6.3 Recommendations and Future Work

The recommended future work is the investigation of wireless backhaul technologies for rural DSL. This is because in this study it has been discovered that backhauling can sometimes be the most cost sensitive part of networks.

The development of relationships with the telecommunications companies, especially in South Africa, with the tertiary institutions is recommended. This will help in opening the doors for accessing the technical information required for research. That will mean a great contribution on assisting the researchers in coming up with more accurate designs which will be based on existing infrastructures. Most companies at the moment are not the same as those in the developing countries, where technical information is shared.

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