Cost-effective Information and Communication Technology (ICT) Infrastructure for Tanzania

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Submitted for the Degree of Doctor Philosophy in Engineering

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Aug 2010

Acknowledgement

First and foremost, I would like to thank my supervisors Professor Chris R.Chatwin and Dr. Rupert C.D.Young for their help, supervision and all the support, which helped me achieve this research work. I am very grateful to Professor Chatwin for his generous help, contribution, motivation and encouragement for this work. He also supported me with my publications, and reviewed this thesis. Indeed, Professor Chatwin, without your valuable contribution, this work would not have been accomplished, thank you very much!

I would also like to thank my employer, which is the Institute of Finance Management (IFM) in Tanzania for giving me full financial support throughout this research work.

Finally, I am indebted to both my dearest wife Rehema and our beloved sons Yarik and Yaver for their love, support, patience, perseverance and understanding during many days and nights I had to be away from them when I am indeed needed. They all truly share in this accomplishment.

UNIVERSITY OF SUSSEX

DPHIL IN ENGINEERING

COST-EFFECTIVE INFORMATION AND COMMUNICATION TECHNOLOGY (ICT) INFRASTRUCTURE FOR TANZANIA

SUMMARY

The research conducted an Information and Communication Technology (ICT) field survey, the results revealed that Tanzania is still lagging behind in the ICT sector due to the lack of an internationally connected terrestrial ICT infrastructure; Internet connectivity to the rest of the world is via expensive satellite links, thus leaving the majority of the population unable to access the Internet services due to its high cost. Therefore, an ICT backbone infrastructure is designed that exploits optical DWDM network technology, which un-locks bandwidth bottlenecks and provides higher capacity which will provide ICT services such as Internet, voice, videos and other multimedia interactions at an affordable cost to the majority of the people who live in the urban and rural areas of Tanzania. The research analyses and compares the performance, and system impairments, in a DWDM system at data transmission rates of 2.5 Gb/s and 10 Gb/s per wavelength channel. The simulation results show that a data transmission rate of 2.5 Gb/s can be successfully transmitted over a greater distance than 10 Gb/s with minimum system impairments. Also operating at the lower data rate delivers a good system performance for the required ICT services. A forty-channel DWDM system will provide a bandwidth of 100 Gb/s.

A cost analysis demonstrates the economic worth of incorporating existing optical fibre installations into an optical DWDM network for the creation of an affordable ICT backbone infrastructure; this approach is compared with building a completely new optical fibre DWDM network or a SONET/SDH network. The results show that the ICT backbone infrastructure built with existing SSMF DWDM network technology is a good investment, in terms of profitability, even if the Internet charges are reduced to half current rates. The

case for building a completely new optical fibre DWDM network or a SONET/SDH network is difficult to justify using current financial data.

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List of Acronyms

2B1Q	Two binary bits converted into one of four-voltage level
3G	Third generation of cellular network
AAS	Adaptive antenna system
ADM	Add/drop multiplexer
ADSL	Asymmetrical digital subscriber line
AP	Application service
APD	Avalanche photodiodes
ASE	Amplified spontaneous emission
ATM	Asynchronous transfer mode
AWG	Arrayed waveguide grating
BER	Bit-error rate
BLSR/4	Four-fibre bi-directional line switched ring
BOT	Bank of Tanzania
BPSK	Binary phase shift keying
BS	Base station
BWA	Broadband wireless access
CAS	Content application service
CCM	Chama cha Mapinduzi
CDMA	Code-division multiple access
DCF	Dispersion compensating fibre
DCS	Digital circuit switches
DEMUX	Demultiplexer
DFB	Distributed feedback laser
DGD	Differential group delay
DIT	Dar-es-salaam Institute of Technology
DL	Downlink
DMT	Discrete multitone
DSL	Digital subscriber line

DSM	Dar es Salaam
DWDM	Dense wavelength division multiplexing
EASSy	East African Submarine System
E-agriculture	Electronic agriculture
EASCO	East African common service organisation
EAP & TC	East African Posts and Telecommunications Corporation
E-banking	Electronic banking
E-commerce	Electronic commerce
EDFA	Erbium-doped fibre amplifier
E-education	Electronic education
E-heath	Electronic health
ELCT	Evangelical Lutheran church in Tanzania
EMS	Element management systems
E-manufacturing	Electronic manufacturing
E-marketing	Electronic marketing
E-tourism	Electronic tourism
E-transaction	Electronic transaction
FDD	Frequency division duplex
FDMA	Frequency division multiple-access
FFT	Fast Fourier transforms
FWM	Four-wave mixing
Gb/s	Gigabits per second
GDP	Gross domestic product
H-ARQ	Hybrid-automotive repeat request
HDLC	Higher level data link control
HDSL	High-speed digital subscriber line
ICT	Information and communication technology
IEEE	Institute of electric and electronics engineer
IICD	International Institute for Communication and Development
IFM	Institute of Finance Management

IP	Internet Protocol
IRR	Internal rate of return
ISDN	Integrated switched digital network
ISO	International Standard Organisation
ITU-T	International Telecommunication union- Telecommunication
LAN	Local area network
LED	Light emitting diode
LNB	Low noise block converter
LOS	Line of sight
LSP	Label switched path
LSR	Label switched router
Mb/s	Megabits per second
MAC	Medium access control
MAN	Metropolitan area network
MAP	Media access protocol
METRO	Metropolitan
MIMO	Multiple input multiple outputs
MPLS	Multi-protocol label switching
MUX	Multiplexer
NF	Network facility
NLOS	Non-line of sight
NMS	Network Management system
NPV	Net present value
NRZ	Non-return-to-zero
NS	Network service
NZ-DSF	Nonzero-dispersion fibre
OCh	Optical channel
OC	Optical carrier
OFDMA	Orthogonal frequency-division multiplexing
OLT	Optical line terminal

OMS	Optical multiplex section
OOK	On-off keying
OSC	Optical supervisory channel
OSI	Open systems interconnection
OSPF	Open Shortest Path First
OTS	Optical transmission section
OSNR	Optical signal to noise ratio
OXC	Optical crossconnect
PCM	Pulse code modulation
PDU	Protocol data units
PHY	Physical
PMD	Polarization mode dispersion
PMG	Postmaster general
PMP	Point-to-multi point
PPP	Point-to-point protocol
PSDN	Public packet switched data network
PSRC	Parastatal Sector Reform Commission
PSTN	Public Switched Telephone Network
QAM	Quadrature amplitude modulation
QoS	Quality of Service
QPSK	Quaternary phase shift keying
ROADM	Reconfigurable optical add/drop multiplexer
RZ	Return-to-zero
RWA	Routing wavelength assignment
SBS	Stimulated Brillouin scattering
SC	Single carrier
SDH	Synchronous digital hierarchy
SDL	Simple data link
SIDA	Swedish International Development Agency
SLM	Single-longitudinal mode

SNR	Signal-to-noise ratio
SOHO	Small office/home office
SONET	Synchronous optical network
SONGAS	Songo Songo gas supply
SPE	Synchronous payload envelope
SPM	Self-phase modulation
SRS	Stimulated Raman scattering
SS	Subscriber station
SSMF	Standard single mode fibres
STM	Synchronous transport module
STS	Synchronous transport signal
TANESCO	Tanzania electric supply company
TANU	Tanganyika African national union
TAZARA	Tanzania-Zambia railway authority
TBC	Tanzanian broadcasting company
TCC	Tanzania Communications Commission
TCRA	Tanzania Communications Regulatory Authority
TCP	Transmission control protocol
TDD	Time division duplex
TDMA	Time-division multiple access
TDM	Time-division multiplexing
TENET	Tanzanian education network
TFMF	Thin-film resonant multicavity filter
TP&TC	Tanzania Posts and Telecommunication Corporation
TPC	Tanzania postal services
TPDF	Tanzania people's defense force
TRA	Tanzanian revenue authority
TRC	Tanzania railway corporation
TTCL	Tanzania Telecommunication Company Limited
UDSM	University of Dar-es-Salaam

UL	Uplink
VAT	Value added tax
VCI	Virtual circuit identify
VDSL	Very high-speed digital subscriber line
VLSI	Very-large-scale-integration
VOIP	Voice over Internet protocol
VPI	Virtual Photonics
VSAT	Very small aperture terminal
WDM	Wavelength division multiplexing
WiMAX	Worldwide interoperability for microwave access
WirelessMAN	Wireless Metropolitan area network
WirelessMAN-SC	Wireless metropolitan area network- single carrier
WLAN	Wireless local area network
XPM	Cross-phase modulation

List of Symbols

B	Bit rate, Gb/s
B_E	Electrical bandwidth, GHz
B_O	Optical bandwidth of the receiver, GHz
BER	Bit error rate, 10^{-9} to 10^{-15}
D_{PMD}	Fibre Polarization mode dispersion (PMD) parameter, ps/$\sqrt{km}$
D (ps/nm)	Chromatic dispersion, ps/nm
ε	Crosstalk signal power, dB
G	Erbium-doped fibre optical amplifier (EDFA) gain
h	Planck's constant, J/Hz
k	Number of fibre spans
L	Fibre link length, km
L_{span}	Product of the span loss, dB
M	Fibre span
N	Interfering wavelength channels in the DWDM system
N_{amp}	Number of EDFA spans
NF	Noise figure of the EDFA, dB
OSNR	Optical signal to noise ratio, dB
P_{ASE}	Amplified spontaneous emission (ASE) power, mW
P_{in}	Optical signal input power, dB
P_{out}	Optical signal output power, dBm
PP	Power Penalty, dB
SNR	Signal to noise ratio, dB
T	Bit Period, ns or ps
v	Optical frequency, THz
W	Wavelength channel, nm
θ_c	Critical angle, radians
α	Fibre attenuation, dB/km
Δ_{Γ}	Differential group delay (DGD)

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CHAPTER 1. INTRODUCTION

1.1. Telecommunication revolution

Telecommunication is the assisted transmission of signals over a distance for the purpose of providing information. The telecommunications period began during the French revolution on August 15, 1794 when the first message was transmitted with the optical telegraph developed by Frenchman Claude Chappe [1]. The following decades witnessed the growth of telecommunications as both wire and wireless technologies were developed, first using copper wire and high-frequency radio, and then adding coaxial cable, microwave, satellites, and optical networks [2]. The 20th century has made these technology advances available in most places of the world. Today, the telecommunications environment is changing dramatically, driven by technological innovation after the convergence of telecommunications and information technologies that resulted in a new sector of information and communication technology (ICT) [2]. ICT has contributed to the enormous increase in the capacity of infrastructures; for example, nowadays, an optical network can transmit more than 100,000 voice channels or Terabits per second data rate on one channel [3-5]. Contemporary ICT infrastructure is also capable of delivering bandwidth in a flexible manner where and when needed. Optical networks offer much higher bandwidth than other networks and are less susceptible to various kinds of electromagnetic interferences and other undesirable effects. Hence, optical networks are the preferred ICT infrastructure for transmission of data at anything more than a few tens of megabits per second over any distance more than a kilometer [3-5]. Optical network technology has evolved over the past few decades to offer higher and higher data rates over longer and longer distances. The increase ICT infrastructure transmission capacity has enabled the transition from analog to digital communication. Data in digital form can be transmitted through ICT infrastructures, stored and accurately retrieved. Digitisation offers the ability to compress the signal in order to reduce bandwidth requirements, thereby increasing even more the capacity of ICT infrastructures to transmit information [6-8].

1.2. The ICT role onto socio economic development

ICT infrastructure plays a vital role in the social, political, and economic development of every country; hence it is similar to motorways in the fifties, electricity at the beginning of the century and railways in the nineteenth century [9]. Many studies have indicated that there is a high positive correlation between economic development and ICT infrastructure investment [2]. Countries invest more in ICT infrastructures as their economies grow; there is evidence that investment in ICT infrastructure can itself contribute to socio-economic development [2]. ICT infrastructure is being used to deliver ICT service where it is needed, when it is needed, and in its most useful form. As a result ICT is playing an increasingly significant role in business activities from research and development to manufacturing, finance, banking, marketing, shipping and education [10]. For example [11], the role of ICT in socio-economic development is illustrated by the impact of the Netscape web browser, which was launched in 1994. From this year to year 2000, the number of web hosts grew from 2.2 millions to over 400 million, 40 percent of these in North America and half divided almost evenly between Europe and Asia/Pacific. Thousands of new firms were created and stocks markets boomed.

Since then, ICT promised a new economy. It caused radical changes in labour markets, a change in cultural expectations and exploration and the introduction of new products and services. The entry of new firms into these new economic spaces shook the strategies and fates of industrial and financial giants [11]. In this regard, the ICT revolution resulted in a cognitive reframing of work and entrepreneurship that vies with traditional job definitions and aspirations of labour market participants. ICT linked manufacturers with assembly plants, designs with factories, software engineers with hardware vendors, suppliers with retailers and retailers with customers. Nowadays, it is not necessary to have all the expertise in-house; by the use of ICT, freelance designers can now send clothing patterns directly to an automated garment factory; and customers can order anything from airline tickets to winter clothing online and do their own banking and pay bills electronically [11]. Furthermore, ICT opens global markets to the small business and allows low-budget, nonprofit organisations to reach interested parties across the countries or the world. For example [2], an agricultural cooperative can use computer terminals to find where to get the best prices for their crops and tourist lodges in rural areas can book reservations. Using the ICT, Researchers can access journals or proceedings of conferences online. The ICT also enable students far from universities to take open learning studies and take exam assignments and exams online. Even employees can keep their knowledge up-to-date through continuing education delivered to their workplace.

Moreover, ICT contributes to health care delivery by enabling health workers in the field to consult with experts and medical researchers around the world to share information. ICT also offers opportunities for people to communicate and help each other through online communities. Furthermore, ICT can enable development workers and journalists in the field to send reports by using email; these materials later could be edited and published in newspapers in the city. Newsletters also could be attached and sent by email either directly to the communities or to regional centres for duplication and dispatch to communities or schools and clinics in their territory. Government or private organisations can conduct business from virtually any location. For example, Banks can transfer funds internationally using a SWIFT network. People can use cash machines (i.e. ATM) anywhere in the world to withdraw money at the bank cash point. Also brokers and traders can buy and sell different things online [2].

1.3. ICT economic impact in developing countries

The economic impact of ICT in developing countries can be particularly significant in rural areas, where alternative means of obtaining and conveying information, such as personal contact, transport and postal services, are less accessible. As developing countries join the global market e.g. by attracting multinational corporations, establishing joint ventures and developing service industries; they soon recognise the need for a reliable and modern ICT. ICT has a significant social and economic impact on modern society [2], [9-11]. For example, the studies conducted by [12-14] indicate that ICT can contribute to economic growth, not only in developed countries, but also in developing countries (i.e. Asian or African countries). For example in Africa, ICT can contribute to socio-economic development such as health services. Doctors can get information on diagnosis and treatment of some cases, beyond their level of expertise, or a patient can benefit if the health worker at a rural clinic can get advice from a doctor at a regional hospital; farmers can have access for coffee, cashew nuts, sisal and tea futures prices on the world trading market; government tourism offices can advertise safari parks and other tourist places via the Internet and fish exporters can easily fill orders faxed from Europe or America and get their money through E-transaction via any bank in their country. Also farmers in a village can benefit if an agricultural officer contacts an agronomist to find out how to eliminate a crop disease.

Anywhere in a world, ICT should be considered a vital component in the development process that can improve productivity and efficiency of rural agriculture, industry and social services, which can enhance the quality of life in developing countries. It also complements other development investments e.g. electricity, transportation, water etc [9]. However Tanzania, which is located in East Africa, still lags behind the rest of the world in ICT despite its ICT policy [15] that provided guidelines for the country to become a hub of ICT infrastructure and use ICT solutions to enhance its socio-economic development. In this regard to close the digital divide with other countries and enhance sustainable socio-economic development and accelerate poverty reduction in the whole country is a national priority.

To enable this transition a high capacity internationally connected Tanzanian ICT backbone infrastructure that exploits optical dense wavelength division multiplexing (DWDM) network technology is conceived in this research.

1.4. The objectives and outline of the thesis

The objective of this research is to design a cost-effective ICT backbone infrastructure that exploits optical DWDM network technology, which will un-lock bandwidth bottlenecks and provide higher capacity which will provide ICT services such as Internet, voice, videos and other multimedia interactions at an affordable cost to the majority of the people who live in the urban and rural areas of Tanzania. The research first focuses on an ICT site survey of Tanzania in order to understand the status of existing ICT infrastructure and ICT services in Tanzania. The political and commercial backdrop, and legislative background of the ICT industries are also assessed. The Optical DWDM network is designed and optimised for low cost, reliability and bandwidth, in which the performance of a DWDM network is assessed using VPI simulation software. The optical DWDM network is designed using some existing (existing but not integrated) standard single module fibres, the costs for such a system are compared with new build DWDM and SONET/SDH networks. The research performs economic analysis for payback and net present value of each network. Furthermore, sensitivity analysis is used to analyse uncertainties that may occur due to the parameter variations during development stages of either DWDM networks or SONET/SDH. Tanzania does not currently have an existing integrated fibre optical backbone; it only has point-to-point standard single mode fibres that belong to different companies and government organizations.

Chapter 1 is an introductory chapter, which explains a revolution of telecommunications that resulted to the ICT sector. Thereafter, the role of ICT in socio economic development is discussed in detail and, finally, the ICT economic impact in developing countries is revealed, followed with the research objectives.

Chapter 2 presents a general overview of the ICT infrastructures that are used to transmit ICT services from one place to another and also exposes their limitations.

Chapter 3 provides Tanzanian background information and its historic perspective of telecommunications. Then liberalisation of telecommunication in a country is discussed and, finally, an ICT survey for Tanzania is presented.

Chapter 4 firstly introduces an ICT backbone infrastructure concept that exploits optical DWDM network technology. Secondly the deployment considerations and economic aspects of the optical DWDM network technology are quantified. Thereafter it demonstrates the implementation of an optical DWDM network for the ICT backbone infrastructure in Tanzania. Afterwards the chapter reveals the optical components that are being used in the DWDM network. Then it describes how data (e.g. Internet traffic) is transmitted in the ICT backbone infrastructure. Finally, it demonstrates the access network, which is installed at the edge of the DWDM network and how it provides ICT services to the majority of the people who live in both urban and rural areas.

Chapter 5 first analyses various system impairments, which occur in the DWDM system when transmitting the signal on the standard single mode fibres (SSMFs) for the Tanzanian ICT backbone infrastructure deployment. Also it discusses the measurements which are used to determine the signal loss due to the system impairments in DWDM systems and, finally, it analyses and compares the performance of the DWDM system when data rates of 2.5 Gigabits per second (Gb/s) and 10Gb/s are transmitted over both short and long distances of SSMFs in the ICT Backbone.

Chapter 6 presents a cost analysis study to justify the economic worth of incorporating existing optical fibre installations into an optical DWDM network for the creation of an affordable ICT backbone infrastructure; this approach is compared with building the ICT backbone using a completely new optical fibre DWDM network or a SONET/SDH network.

Chapter 7 finalises the thesis by providing conclusions and a brief review of the contribution of this research in the field. It also makes suggestions for future research.

The results described in chapters 3, 4, 5 and 6 have been published as two conference papers and 4 journals articles. A publication list can be found on appendix 1, page 148.

CHAPTER 2.OVERVIEW OF ICT INFRASTRUCTURES

2.1. Introduction to Public Switched Telephone Network (PSTN)

The PSTN provides a worldwide grid of connections that enable point-to-point communication between many telephone subscribers. The PSTN is made flexible and efficient by the use of switching. A switching exchange hierarchy (Figure 2.1) begins with the local exchanges [16]. Every customer (telephone subscriber) has a dedicated switched circuit feeding into the local exchanges that are connected in a tiered fashion by copper cables. Thus many local exchanges feed into higher-level tandem exchanges, which are cross-connected, and so on until they connect to the international tandem exchanges (i.e. backbone). The whole hierarchical design is based on the probability of a call; the higher the probability, the lower the tier through which the call is routed.

The early PSTN systems used electromechanical switches and then analogue switching to provide telephone call routing over a copper telephone line. However the rapid advance of digital technology has overtaken analogue switching and, nowadays, almost all PSTN uses digital switching circuits to transmit data over the existing copper telephone lines (twisted-pair) [1], [6-8]. The following section describes the public digital switched circuit network that use copper telephone lines to transmit ICT services from one location to another in developed and developing countries.

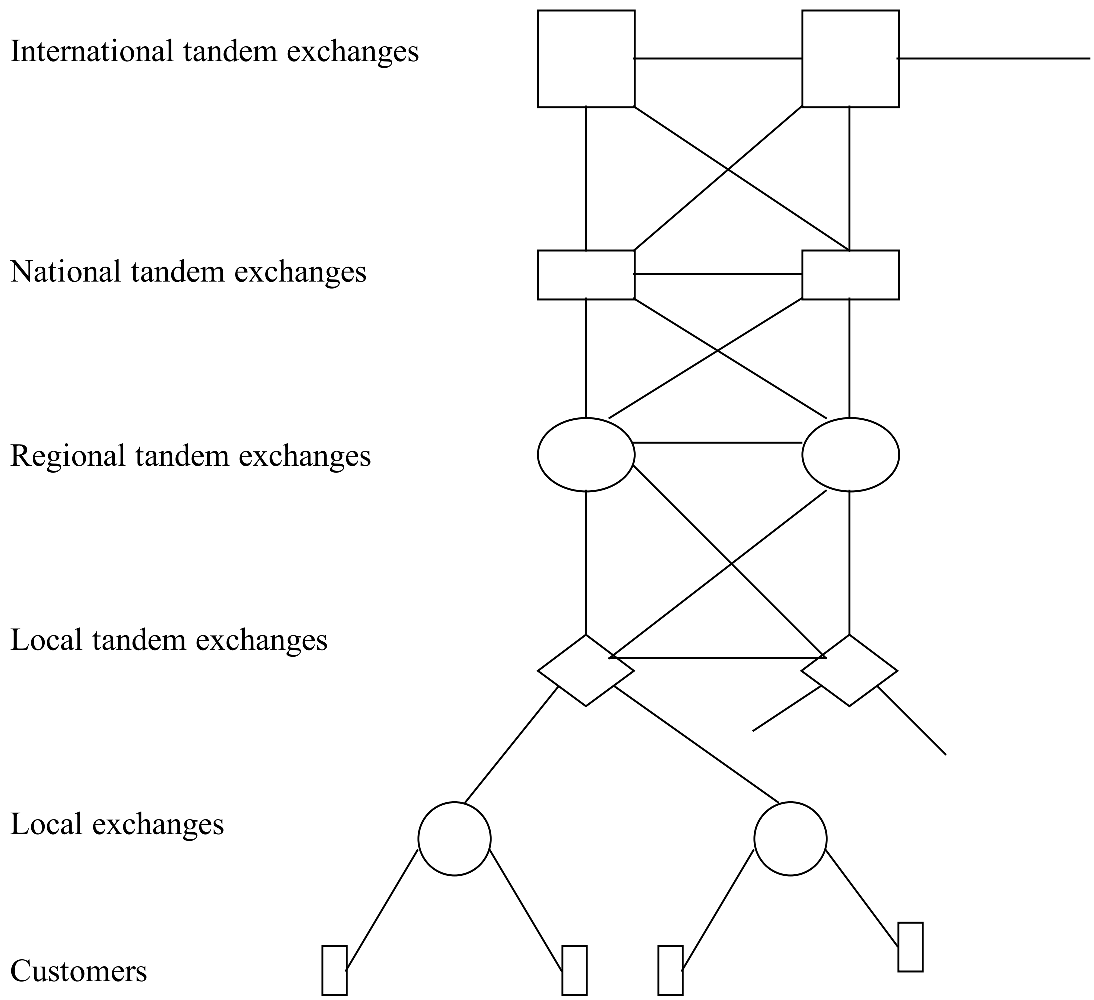

Figure 2.1: A switching exchange hierarchy diagram [16]

2.1.1. Integrated switched digital network (ISDN)

An ISDN network uses digital switching and was originally upgraded from analogue public switched telephone network (PSTN) to support a wide range of ICT services such as voice, data, fax and multimedia through the copper telephone line [1], [6], [7], [16-18]. In an ISDN network, the audio voice frequency of 4 KHz is digitised at an 8 kHz sample rate using 8-bit pulse code modulation (PCM). This leads to a transmission bit rate of 64 Kb/s. ISDN uses this transmission rate for its base transmission rate. Thus, computer data can be transmitted using this bit rate or can be split to transmit over several 64 Kb/s channels. The basic data rate (Basic access) for ISDN services use two 64 Kb/s channels and a 16 Kb/s control line to transmit data over a copper telephone line. In analogue PSTN network, the customers (subscribers) were limited to the maximum bit rate of 56 Kb/s (i.e. dial-up

Internet service) to transmit data. However with ISDN, the customers can use a data rate of more than 128Kb/s. Also multiple channels can be transmitted on a coaxial cable in the ISDN network. For example, in America and Europe multiple channels of 24 and 32, respectively, each carrying a bit rate of 64 Kb/s, are multiplexed together using time-division multiplexing (TDM) technology on a coaxial cable. These form a bandwidth of 1.544 Mb/s and 2.048 Mb/s data rates, respectively; this is known as primary data rate (Primary access). Figure 2.2 below shows a block diagram of ISDN systems that illustrates basic and primary access. Since, in an ISDN, a permanent connection is established to the customer, the bandwidth for the required length of the connection is guaranteed.

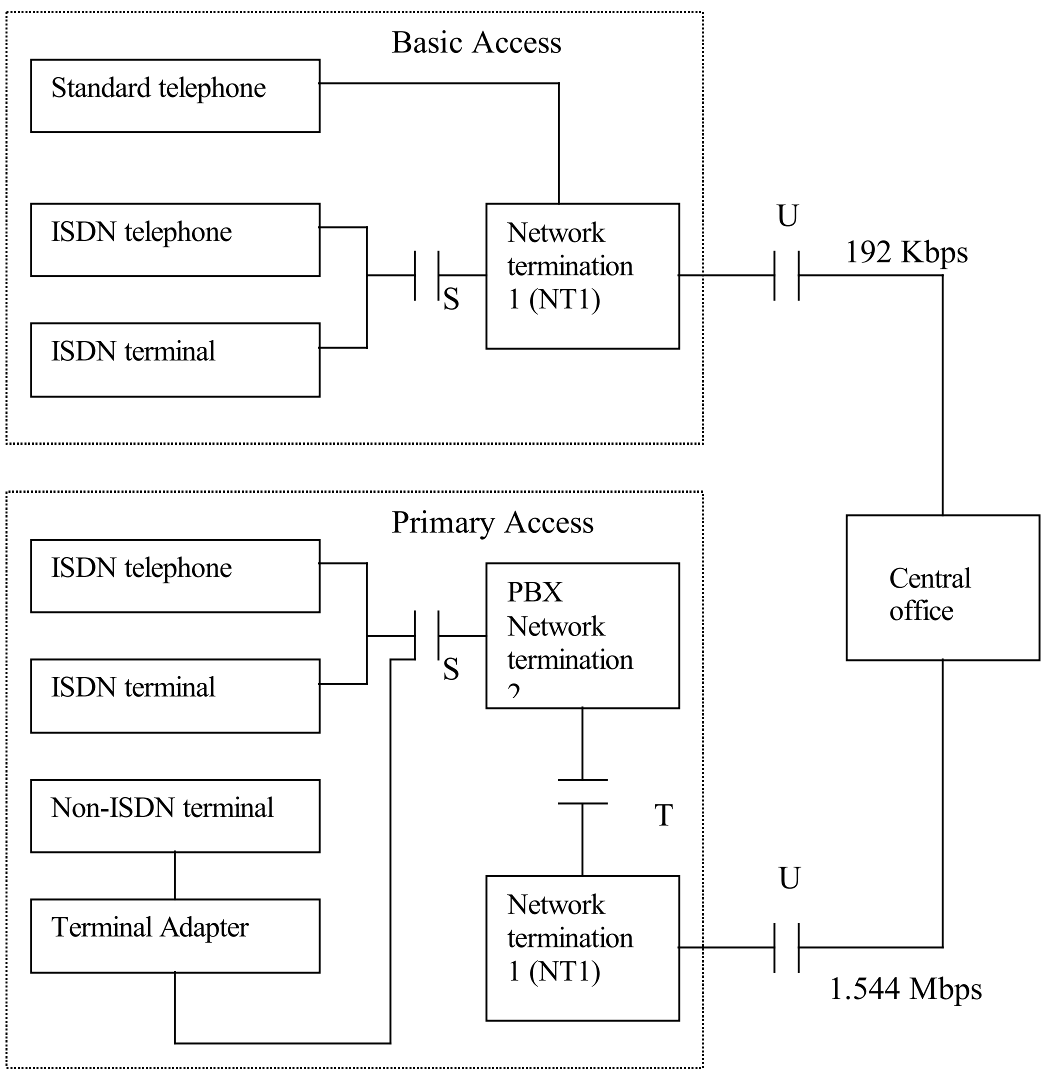

Figure 2.2: Basic and primary access ISDN system [6]

2.1.2. Digital subscriber lines (DSL)

DSL networks also use digital circuit switches to provide a means of extending a data rate of 1.5 Mb/s or more by using copper telephone line from the telephone exchanges (usually between 2 and 5 km in Europe and 4 to 8 km in the United States) to the customer premises. Figure 2.3 below shows the block diagram for the DSL system. The following paragraphs present different types of DSL systems [1], [6], [16], which are currently commercially available.

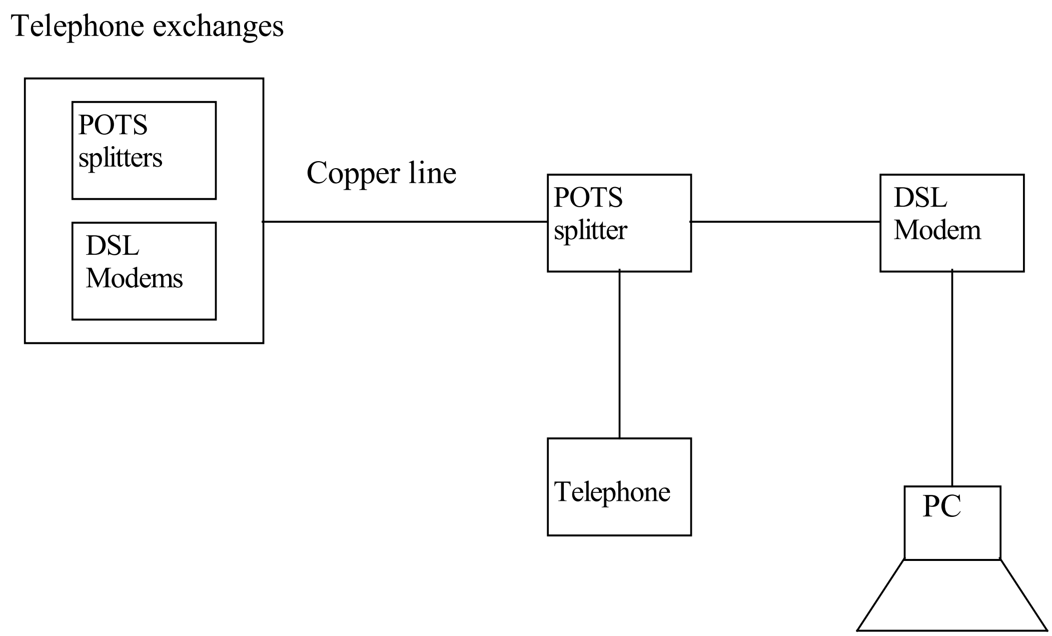

Figure 2.3: DSL system [6]

2.1.2.1. Asymmetrical digital subscriber line (ADSL)

ADSL systems allow the use of an asymmetrical high-speed digital signal on a copper telephone line to the customer premises. The system is asymmetrical because the data rate from the telephone exchange to the customer is much greater than in the opposite direction. ADSL is based on the assumption that the customer needs more bandwidth to receive transmissions (downstream link) than for transmission (upstream link). For this reason, ADSL provides maximum upstream data rates of 1.544 Mb/s and 1.5 to 8 Mb/s as a downstream. ADSL uses a data modulation technique called discrete multitone (DMT), which uses multiple sub-channel frequencies to carry the data [6]. The DMT uses up to 256 sub channel frequencies to carry data over the copper telephone line. Normally a test is initiated at start-up to determine which of the 256 sub-channel frequencies is available to carry the data. The ADSL system then selects the best sub-channel and splits the data over the available sub-channels for transmission.

2.1.2.2. Symmetrical digital subscriber line (SDSL)

SDSL are similar to ADSL but support the full-duplex bi-directional transmission of voice and data to the customer premises at speeds from 128 Kb/s to 2.048 Mb/s over copper telephone lines.

2.1.2.3. Very high-speed digital subscriber line (VDSL)

VDSL supports both symmetrical and asymmetrical data transmission on the copper telephone line. Thus it allows a maximum upstream data rate of about 2 Mb/s and a downstream data rate up to 50 Mb/s; this limits a copper telephone cable to about a 300 m distance. However, limiting the downstream data rate to 28 Mb/s and 13.8 Mb/s can allow a range of 1 km and 1.5 km, respectively.

2.1.2.4. High-speed digital subscriber line (HDSL)

HDSL systems use two pairs of copper telephone cable to transmit data. As a result, the data rate on each pair is reduced and thus allows data to be transmitted up to 5 km on a copper telephone line. The data on each pair is encoded by the 2B1Q method; two binary bits (2B), or dibits, are converted into one of four voltage levels (1Q) [16]. The DC voltage levels are transmitted along each pair and measured at the receiver for decoding back into dibits. Echo cancellation techniques [6], [16] are used to subtract the transmitted signal from the composite signal across the line, thus leaving the received signal.

2.1.3. The limitations of PSTN

The problem of public circuit switching network (PSTN) is that they are not efficient at handling burst data rates (e.g. Internet traffic). Since the Internet traffic varies widely over time, fixed bandwidth circuits like PSTN become inefficient [4], [19]. For example [4], when the user is actively typing from a keyboard, bits are transmitted at more or less a steady rate. When the user pauses, there is no Internet traffic. Another example is Web browsing; when a user is looking at a recently downloaded screen, there is almost no Internet traffic. When he/she clicks on a hyperlink text, a new page will be downloaded as soon as possible from the network. Thus a burst stream requires a lot of bandwidth from the network whenever it is active and very little bandwidth when it is not active. It is usually characterised by an average bandwidth and a peak bandwidth, which correspond to the long-term average and the short-term burst rates, respectively. Since, a PSTN is a fixed connection, it would reserve sufficient bandwidth to deal with the peak rate but this bandwidth would be unused a lot of time. Therefore, a public packet switched data network (PSDN) was invented to deal with the problem of transporting burst data traffic efficiently [8], [20], [21]. The following section describes in detail the PSDN.

2.2. Public Switched Data Network (PSDN)

A PSDN is a packet switching network established specifically for the transmission of data [8]. The International Telecommunication union, Telecommunication (ITU-T) [22], set up the international standard for user data signaling rates and user interfaces in the PSDN. In PSDN, the data stream is broken up into small packets of data. These packets are multiplexed together with packets from other data streams inside the network and the packets are switched inside the network based on their destination. This technique is called statistical multiplexing [7], [8]. To facilitate this switching, a packet header is added to the payload in each packet. The header carries source and destination addressing information; for example, the destination address is the address of the next node in the path. The intermediate nodes read the header and determine where to switch the packet based on the information contained in the header. At the destination, packets belonging to a particular stream are received and the data stream is put back together. The predominant example of a PSDN is the Internet, which uses the Internet Protocol (IP) to route packets from their source to their destination.

2.2.1. Internet Protocol (IP)

IP is used in the all-pervasive Internet and is equally important in most private intranets to link up computers worldwide. This protocol is designed to work above data link and physical layers in the seven-layer of OSI (open systems interconnection) model [23], which was developed by the International Standard Organisation (ISO). Figure 2.4 gives a summary of the function of each layer of the OSI protocol. IP protocol transports information in the form of packets, which are of variable length. An IP router is the key network element of the PSDN, which forwards packets from an incoming link onto an outgoing link. Each router maintains a routing table; the routing table has one or more entries for each destination router in the PSDN network. The entry indicates the next node adjacent to this router to which packets need to be forwarded. An IP packet contains a header and payload. The header carries the information required for routing, such as source and destination node IP address. The payload carries the actual data. The router looks at the header in a packet arriving on an incoming link. The router then does a lookup of its routing table to determine the next adjacent node for that packet and then forwards the packet on the link leading to that node. The most common routing protocol used in PSDN networks is Open Shortest Path First (OSPF) [24-26].

File transfer, access and management, Document and message interchange	Application Layer
Transfer syntax negotiation, data representation transformations	Presentation layer
Dialog and synchronization control for application entities	Session Layer
End-to-end message transfer (control management and error control)	Transport layer
Network routing, addressing, call set-up, and clearing	Network Layer
Data link control (framing, data transparency, error control)	Data link layer
Mechanical and electrical network interface definitions	Physical Layer

Figure 2.4: Summary of each layer function in OSI model [8]

2.2.2. Best-effort services

PSDN network [4], since each data stream is burst, it is likely that at any given time only some streams are active and others are not. The probability that all streams are active simultaneously is quite small. Therefore the bandwidth required on the link can be made significantly smaller than the bandwidth that would be required if all streams were to be active simultaneously. Statistical multiplexing in a PSDN network improves the bandwidth utilisation but leads to some other important effects. If more streams are active simultaneously than the available bandwidth on the link, some packets will have to be queued or buffered until the link becomes free again. The delay experienced by a packet therefore depends on how many packets are queued up ahead of it. This causes the delay to be a random parameter. On some occasions, the traffic may be so high that it causes the buffers to overflow. When this happens, some of the packets must be dropped from the network. Usually, a higher-layer transport protocol, such as the transmission control protocol (TCP) in the Internet, detects this and ensures that these packets are transmitted. On top of this, a traditional packet switched network doesn't even support the notion of a connection. Packets belonging to a connection are treated as independent entities, and different packets may take different routes through the network. This is the case with networks using IP. This type of connectionless service is called a datagram service. This leads to even more variations in the delays experienced by different packets and also forces the higher layer transport protocol to re-sequence packets that arrive out of sequence at their destinations. Thus, traditionally, such a packet switched network provides what is called a best-effort service. The network tries its best to get data from its source to its destination as quickly as possible, but offers no guarantees. This is indeed the case with much of the Internet today.

2.2.3. Frame relay

Frame relay (another example of datagram service) is a popular packet switched network provided by carriers to interconnect corporate data networks [27]. When a user signs up for a frame relay service, he/she is promised a certain average bandwidth over time but allowed to have an instantaneous burst rate above this rate, however without any guarantees. Thus, in order to ensure that the network is not overloaded, the user data rate may be regulated at the input to the network so that the user doesn't exceed their committed average bandwidth over time. In other words, a user who is provided with a committed rate of 64 Kb/s may send data at 128 Kb/s on occasions (e.g. off-peak time), and 32 Kb/s at other times, but will not be allowed to exceed the average rate of 64 Kb/s over a long period of time. This best-effort service provided by packet switched networks is fine for a number of applications, such as Web browsing and file transfers, which are not highly delay sensitive applications. However, applications such as real-time video or voice calls require a constant data rate and must propagate through the network with the minimum of delay.

2.2.4. Virtual circuits

To eliminate the problem of providing best-effort service, another service called virtual circuit was developed. A virtual packet forces all packets belonging to that circuit to follow the same path through the PSDN network, allowing better allocation of resources in the network to meet certain quality of service guarantees, such as bounded delay for each packet. Unlike in a PSTN, a virtual circuit doesn't provide a fixed guaranteed bandwidth along the path of the circuit due to the fact that statistical multiplexing is used to multiplex virtual circuits inside the network. Example of virtual circuits service are Asynchronous transfer mode (ATM) [6-8], [16] and multi-protocol label switching (MPLS) [28-32], which is currently used in IP networks.

2.2.4.1. Asynchronous transfer mode (ATM)

An ATM network is a packet switching technique designed for voice, data, and video traffic [6-8], [16]. An ATM network uses packets (cells) with a fixed size of 53 bytes. A small packet size is preferable for voice since the packets must be delivered with only a short delay. A large packet size is preferable for data since the overheads involved in large packets are smaller. 5 bytes of the 53 bytes in an ATM packet constitute the header, which is the overhead required to carry information such as the destination of the packet. The 48 bytes form the payload, which carry information sent from the higher layers. ATM establishes a connection between two ends points by using a virtual circuit identifier (VCI) for the purpose of transferring data between them. This is unlike IP as discussed above, which transfers data in a connectionless manner. The VCI for a connection is unique for each link that the ATM connection traverses between its end points but can vary from link to link on the path. The VCIs for each connection on every link of the path are determined at the time of the connection setup and released when the connection is released.

2.2.4.2. Multiprotocol Label Switching (MPLS)

MPLS is a new technology in the IP network, which provides a label switched path (LSP) between nodes in the network [28-32]. A router implementing MPLS is called a label switched router (LSR). Each packet now carries a label that is associated with a label switched path. Each LSR maintains a label-forwarding table, which specifies the outgoing link and outgoing label for each incoming label. When an LSR receives a packet, it extracts the label, uses it to index into the forwarding table, replaces the incoming label with an outgoing label, and forwards the packet on the link specified in the forwarding table. The major advantage of MPLS over an IP router is that it introduces the notion of a path in an IP network. IP routers traditionally route packets, or datagrams, and have no notion of end-to-end paths. Different packets between the same pair of routers could take different routes through the network, based on the current state of the routing tables at the routers. The ability of MPLS to specify paths along which packets can be routed has several advantages as follows: An Internet service provider (ISP) owning a network can plan end-to-end routes for packets based on a variety of criteria. For example, it could plan routes to prevent some links from getting congested while other links are idle. The ability to have explicitly routed paths also allows a service provider to offer certain Quality of Service (QoS) assurances for selected traffic, in contrast to an IP router, which offers a best-effort service as mentioned above.

2.3. Satellite communications

Satellite is a wireless based network technology used widely for data transmission applications ranging from interconnecting different telecommunication applications to providing bit rate data communications in different parts of the world [1], [6], [16], [18]. Satellites, which are used for communication purposes are normally geostationary, which means that the satellite orbits the earth once every 24 hours in synchronism with the earth’s rotation and hence appears stationary from the ground. A geostationary orbit is a geosynchronous orbit directly above the earth’s equator (0^{o} latitude), with a period equal to the earth’s rotational period and an orbit eccentricity of approximately zero.

The geostationary orbit is useful for communications applications because the earth satellite station, which is called very small aperture terminal (VSATs) are directed toward the satellite, and can operate effectively without the need for expensive equipment to track the satellite motion. A geosynchronous orbit is an orbit around the earth with an orbit period matching the earth rotation period. The orbit of the satellites is chosen so that it provides a line of sight communication path to the transmitting stations and receiving stations. The degree of collimation of the microwave beam retransmitted by the satellite can be either coarse, so that the signal can be picked up over a wide geographical area, or finely focused, so that it can be picked up over only a limited area. Satellites transmit the signal by using electromagnetic (radio) waves through free space. A collimated microwave beam, onto which the signal is modulated, is transmitted to the satellite from the earth station (Figure 2.5). This beam is received and transmitted (relayed) to the predetermined destinations using an on-board circuit known as a transponder.

A single satellite has many transponders each covering a particular band of frequencies. Transponders perform reception, frequency translation, and retransmission of signals. The frequencies for satellite communication systems range from 1 GHz up to 40 GHz [6]. The early satellite systems used frequency division multiple-access (FDMA) technology [1], [6], [17], [18], in these systems; the satellite used a wideband receiver/transmitter that includes a number of frequency channels. The earth stations had to send a control signal to identify the available frequency channel for signal transmission. Once the transmission process is complete, the frequency channel is released. Nowadays, most Satellite systems use either a code-division multiple access (CDMA) or time-division multiple access (TDMA) technologies [1], [6], [17], [18]. In CDMA, each earth station (i.e. VSAT) uses a different binary sequence to modulate the carrier. With TDMA techniques, all earth stations (i.e. VSAT) use the same carrier frequency, but they transmit one or more traffic bursts in non-overlapping time frames. For example Figure 2.5 below show three VSATs (earth station 1, 3 and 4), which are transmitting simultaneously but never at the same instant of time by using the TDMA technique. The traffic bursts are amplified by the satellite transponder and retransmitted in a downlink beam that is received by the desired VSAT (terminal 2). TDMA offers the following advantages over FDMA systems [6]:

- A single carrier for the transponder to operate on is a major advantage. Its power amplifier is much less subject to intermodulation problems and can operate at higher power output when dealing with a smaller range of frequency.

- The use of the time domain rather than the frequency domain to achieve multiple channels is advantageous. In FDMA, the earth station must transmit and receive on a multiplicity of frequencies and must provide a large number of frequency-selective up-conversion and down-conversion chains. In TDMA, channel selection is accomplished in the time domain rather than frequency. This is much simpler and less expensive to accomplish.

- TDMA is ideally suited to digital communications since they are naturally suited to the storage, rate conversions, and time-domain processing used in TDMA implementation. Additionally, TDMA is ideal for demand assigned operation, in which the traffic burst durations are adjusted to accommodate demand.

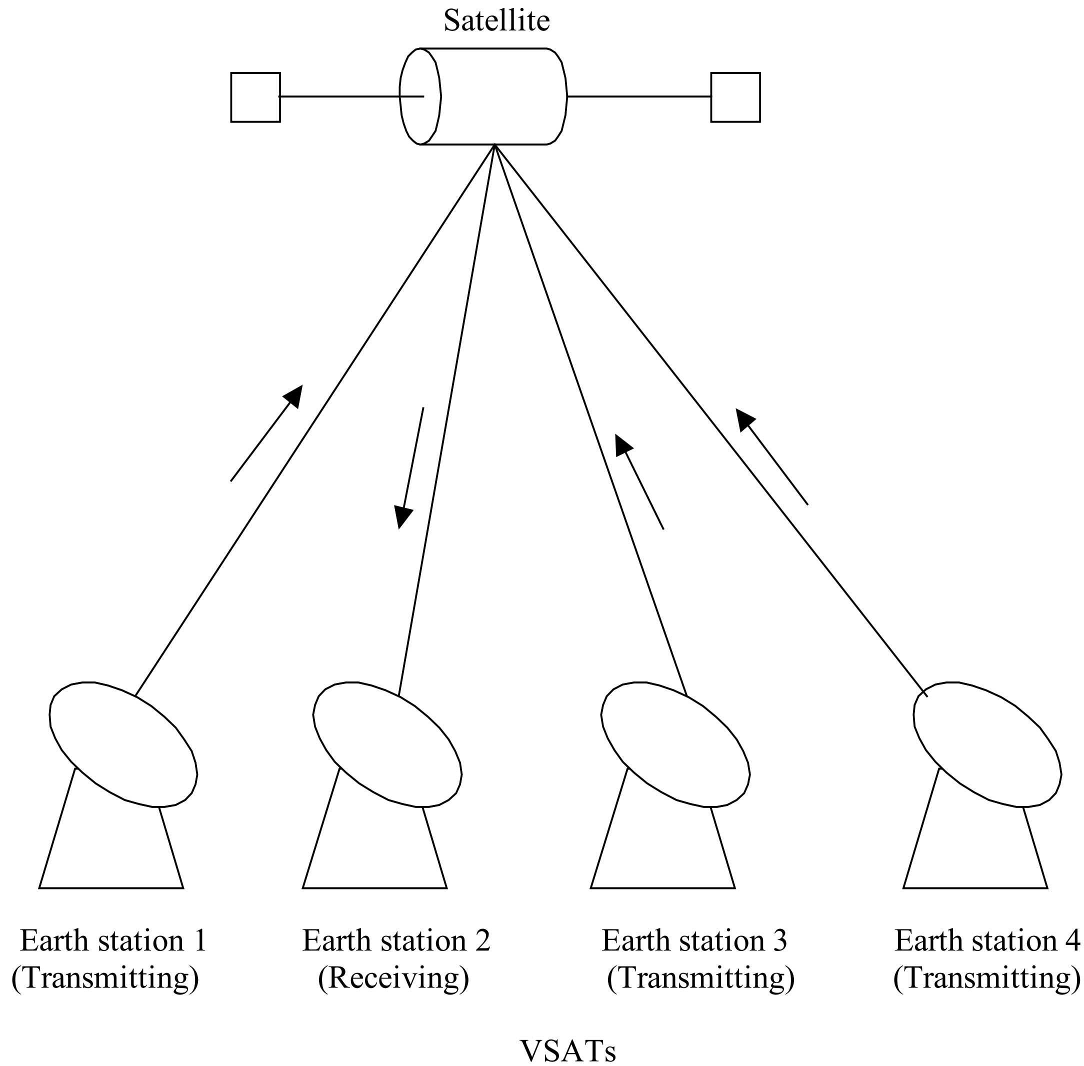

Figure 2.5: TDMA illustration [6]

2.3.1. Very small aperture terminal (VSAT)

The VSAT is a two-way satellite earth station with a dish antenna that is smaller than 3 metres. Most VSAT antennas range from 75 cm to 1.2 cm. VSAT transmit data rates that range from narrowband up to 4 Mb/s. VSAT access satellites in a geosynchronous orbit to relay data from small remote earth stations (terminals) to other terminals in a mesh or star configurations. VSAT operates in the C-band (4/6 GHz), Ku band (12/14 GHz) or Ka band (20/30 GHz) frequency ranges. For communications between satellite and VSAT, a very small portion of a satellite transponder is used for each VSAT return path channel. Each VSAT terminal is assigned a frequency for the return path, which it shares with other

VSAT terminals using a TDMA technique. TDMA allows several VSATs to share the same frequency channel by dividing the signal into different time slots (Figure 2.5).

The broad coverage area of VSAT makes Satellites ideal for many forms of communication, for example, point-to-multipoint data and video. In this regard, it is a major international communications link for voice and data, especially for many developing countries without reliable terrestrial links to the rest of the world. This ability to transmit from virtually any location using VSAT has made satellites extremely useful for multipoint interactive networks. VSAT is typically used for data or voice communication when there is no access to terrestrial networks such as PSTN/PSDN or optical networks, especially in developing or poor countries.

2.3.2. Limitations of satellite communication

Transmission of signals in satellites communications is affected by moisture and rain. The effects are less at lower frequencies; L and C band, but become quite severe at higher frequencies bands such as the Ku and Ka band. For Internet services in tropical areas with heavy rain, C band (4/6 GHz) with circular polarization is normally preferred. For the Ka band (19/29 GHz) special techniques such as large rain margins adaptive uplink power control and reducing bit rates during rain must be applied. The amount of time for which service is lost can be reduced by increasing the size of the dish so as to gather more of the satellite signal on the downlink and producing a more powerful transmission on the uplink, but this increases cost.

Satellite communication also experiences high latency due to the signal having to travel 35,000km (22,000miles) out into space to a satellite in a geostationary orbit and back to earth again. Latency is the delay between requesting data signal and getting a response, or in the case of one-way communication; between the actual moment of broadcast and the time actually received at the destination. The signal delay can be as much as 500 to 900 milliseconds, which makes the satellites communication ineffectual for real time applications, such as online games, VOIP, video conferencing etc.

Furthermore, Satellites operating above 2 GHz are sensitive to even minor obstructions such as the leaves of trees. For this reason a clear line of sight between a VSAT and the satellite is required. Thus, in developed countries, voice telephone service is mostly provided by terrestrial network (wired cabled network) except in remote areas. However, in developing countries, satellite is important for the provision of voice and data services to both urban and rural areas, as well as in television distribution because there are no existing terrestrial networks.

2.4. Worldwide interoperability for microwave access (WIMAX)

WIMAX is also a wireless based communication network technology that provides high data rates and also has the capability to address broad geographical areas without the cost of the infrastructure required to deploy a wired cable network to individual sites. WIMAX [33] offers an alternative to cabled access networks, such as fibre optical links, ISDN and DSL links. In the past few years, the IEEE 802.16 working group [34] has developed a number of standards for WiMAX networks. The first IEEE standard 802.16 [35] was published in 2001, it aimed to support communications in the 10-66 GHz frequency band; whereby a line of sight (LOS) was required between a base station (BS) and subscriber station (SS).

In 2003, the second IEEE standard 802.16a [36] was introduced to provide additional physical layer specifications for the 2-11 GHz frequency band; this allowed the possibility of non-loss (NLOS) operation between a BS and a SS. Then in 2004, these two IEEE standards were combined to form IEEE standard 802.16-2004 (fixed WiMAX)[37] to support fixed broadband wireless access (BWA) in the frequency band from 2-66 GHz frequency band. In Dec 2005, the fixed WiMAX was upgraded to IEEE standard 802.16e [38] to provide both fixed and mobile broadband access that supports subscriber stations operating in licensed bands below 6 GHz. The IEEE standard 802.16e provides the ability to offer a wide range of new and revolutionary high-speed mobile wireless applications and services that greatly improve communication quality. At the time of writing there are more IEEE standards for mobile WiMAX, which have been proposed but are not yet commercially available. The following paragraphs describe only the IEEE 802.16-2004 (fixed WiMAX) and the IEEE standard 802.16e (Mobile WiMAX).

2.4.1. Fixed WiMAX

The fixed WiMAX provides the interoperable air interface from 2 to 66 GHz using the medium access control (MAC) layer as shown in Figure 2.6 to support multiple services (e.g. IP, ATM, Ethernet etc) in a mandatory point-to-multi point (PMP) and optional mesh topology [39]. In PMP topology, a centralised BS controls all communication among the SSs and the BS, whereas in the mesh topology, SSs can serve as routes by cooperative access control in a distributed manner [39]. In a downlink subframe of PMP topology, the BS transmits a burst of MAC protocol data units (PDU) using time-division multiplexing (TDM). In an uplink subframe, an SS transmits a burst of MAC PDU to the BS using time-division multiple access (TDMA). In PMP, multiple SSs share a common uplink to the BS on a demand basis. This means that if an SS needs some amount of bandwidth, it makes a reservation with the BS by sending a request. On accepting the request from an SS, the BS scheduler determines and grants it a transmission opportunity in time slots by using some centralised scheduling algorithms [37], which take into account the requirements from all the authorised SSs and the available channel resources. The main difference between the PMP and an optional mesh topology is that; in the PMP, traffic only occurs between the BSs and SSs, while in the mesh, traffic can be routed through other SSs and can occur directly between SSs [37]. Depending on the transmission protocol algorithms used in Mesh architecture, this can be done on the basis of equality using distributed scheduling, or on the basis of superiority of the mesh BS, which is centralised scheduling, or on a combination of both. The PMP topology provides better quality of service (QoS) performance than distributed mesh topology; hence, it is the preferred WiMAX technology for providing fixed broadband access residential and commercial buildings.

The PHY layer in the 10-66 GHz band is based on a single carrier modulation referred to as a Wireless metropolitan area network- single carrier (WirelessMAN-SC) air interface that requires a LOS transmission due to the larger operation frequency. In the 10-66 GHz band, channel bandwidths of 25 MHz or 28 MHz are typical. With data rates in excess of

120 MB/s, it is suited for PMP access serving applications from a small office/home office (SOHO) through medium to large office applications [39]. The following PHY air interfaces are specified in the lower frequency bands of 2-11 GHz [39]:

- WirelessMAN-SC; uses a special single carrier modulation format, designed for NLOS operation.
- WirelessMAN-OFDM; uses orthogonal frequency-division multiplexing (OFDM)[40] with 256 carriers.
- WirelessMAN-OFDMA; uses orthogonal frequency division multiplexing access (OFDMA) with a total of 2048 carriers.

For this reason, a 2-11 GHz band supports NLOS transmission as well as additional PHY functionality such as the support of advanced power management techniques, interference mitigation/coexistence, and multiple antennas are added. In this band, a variable channel bandwidth is defined that can be an integer multiple of 1.25 MHz, 1.5 MHz, and 1.75 MHz, but no more than 28 MHz [37]. Also, it can support data rates up to 75 Mb/s in both PMP and Mesh architecture.

Furthermore, in the fixed WiMAX PHY layer [37], Different levels of modulation schemes, including binary phase shift keying (BPSK), quaternary PSK (QPSK), 16-quadrature amplitude modulation (QAM), and 64-QAM also can be chosen depending on the channel conditions. Furthermore, optional features of intelligent adaptive antenna systems (AASs) are also allowed to improve the spectral efficiency of the system.

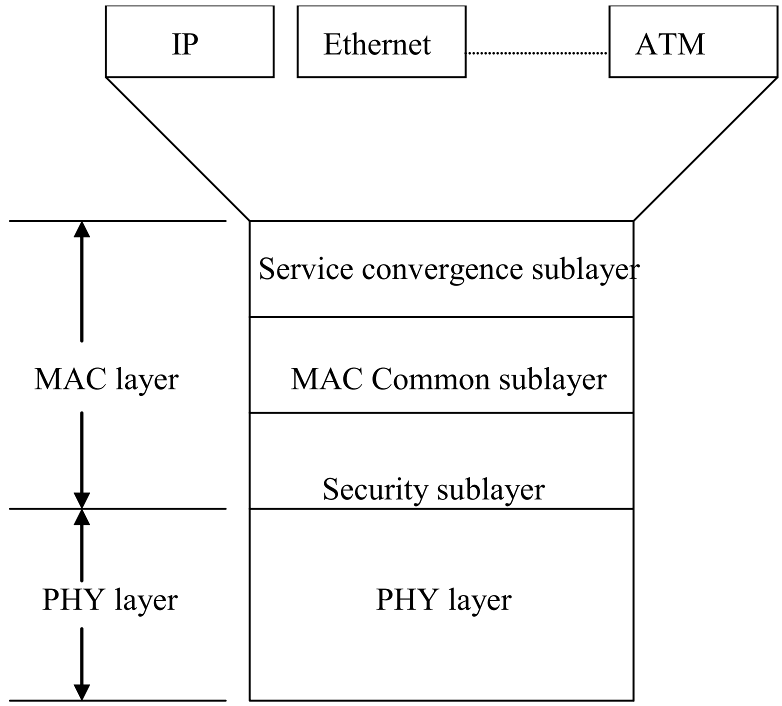

Figure 2.6: Protocol architecture of IEEE 802.16 fixed WiMAX network [39]

2.4.2. Mobile WiMAX

Mobile WiMAX is a fast growing broadband access technology that enables low-cost mobile Internet applications with also the convergence of mobile and fixed broadband access in single air interface and network architecture. Mobile WiMAX combines OFDMA and advanced multiple input multiple output (MIMO) schemes along with flexible bandwidth and fast link adaptation, creating a highly efficient air interface that exceeds the capacity of existing and evolving 3G (Third generation of cellular network) [41]. For example 3G supports a downlink up to 14.4 Mb/s and an uplink up to 5.76 Mb/s while mobile WiMAX technology supports a downlink up to 37 Mb/s and an uplink up to 10 Mb/s [42]. Moreover Mobile WiMAX networks have been built on all IP network architecture for plug and play network development that supports a mix of different usage and service models [41] as shown in Figure 2.7. As mentioned above, Mobile WiMAX employs OFDMA technology in its PHY layer air interface to support mesh and point-to-multi point (PMP) architectures in non-line-of-sight (NLOS).

OFDMA is a multiple access scheme in which data streams from multiple users are orthogonally multiplexed onto downlink (DL) and uplink (UL) sub-channels/sub-carriers [40]. Thus, Mobile WiMAX with the use of OFDMA employs a large fast Fourier transform (FFT) size (2048 and 4096 sub-carriers) that is further divided into sub-channels [43]. The sub-channels are introduced to separate the data into logical streams in DL. Those streams employ different modulations, coding schemes, and amplitude levels to address sub-carriers with different channel characteristics.

The sub-channels also are used for multiple accesses in UL. The subscribers are assigned to sub-channels through media access protocol (MAP) messages sent in downstream. OFDMA also enables smart antenna operations to be performed on vector flat sub-carrier based on smart antenna technologies that typically involve complex vector or matrix operations on signals due to the use of multiple antennas. Furthermore, Mobile WiMAX based on OFDMA technology supports both time division duplex (TDD) and frequency division duplex (FDD) modes in its PHY layer. For TDD mode [43], the system transmits the data frame-by-frame, and each 5-ms frame consists of a DL sub-frame and an UL sub-frame to prevent collisions between DL and UL transmissions. Adaptive modulation, fast channel feedback and link adaption, coding, and asynchronous hybrid-automotive repeat request (H-ARQ) in DL and UL are used also in the Mobile WiMAX to enhance its coverage and capacity.

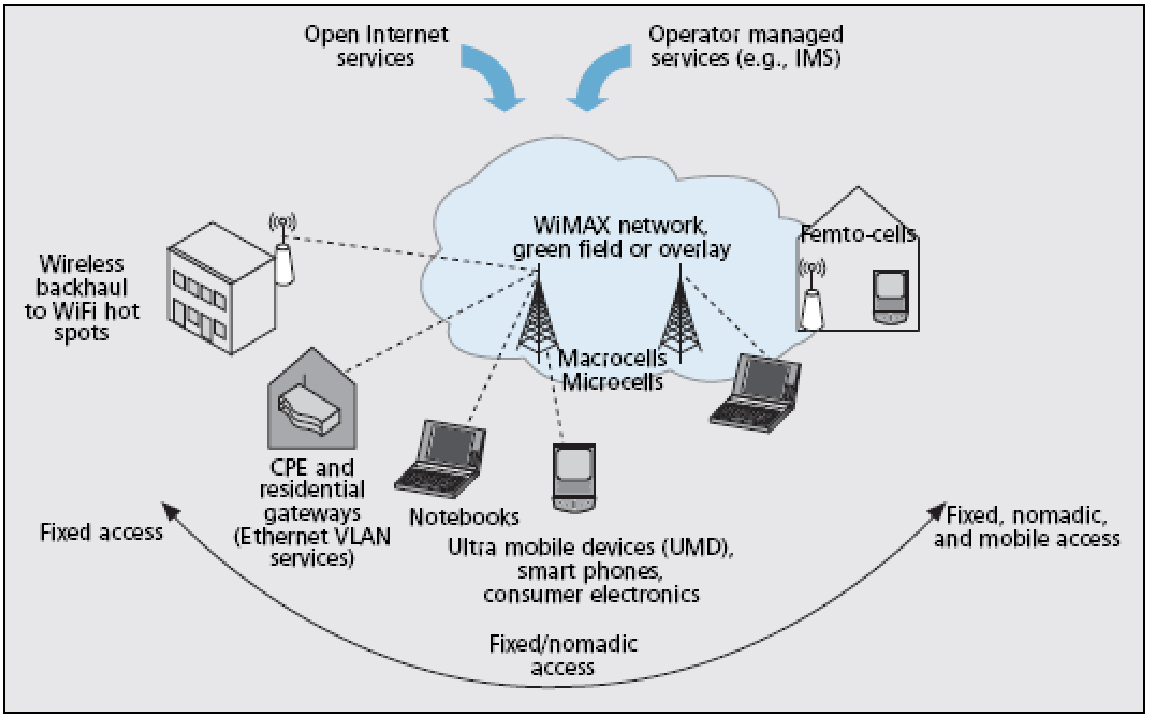

Figure 2.7: Mobile WiMAX enabling a variety of usage and service models in the same network [41]

2.4.3. OFDM Transmission scheme

The basic principle of Orthogonal Frequency Division Multiplexing (OFDM) is to split a high-rate data stream into a number of lower rate streams that are transmitted simultaneously over a number of sub-carriers [40]. Because the symbol duration increases for the lower parallel sub-carriers, the relative amount of dispersion in time caused by multipath delay spread is decreased. Intersymbol interference is eliminated completely by introducing a guard time in every OFDM symbol. In the guard time, the OFDM symbol is cyclically extended to avoid intercarrier interference [40]. Briefly, OFDM is a special form of multi-carrier transmission, where a single high-speed data stream is transmitted over a number of lower-rate sub-carriers. One of the main reasons to use OFDM is to increase the robustness against frequency selective fading or narrowband interference. In a single carrier system, a single fade or interferer can cause the entire link to fail, but in a multi-carrier system, only a small percentage of the sub-carriers will be affected. Error correction coding can then be used to correct for the erroneous sub-carriers [40]. OFDM technology has been an attractive choice for commercial high-speed broadband wireless communications systems, due to recent advances in very-large-scale-integration (VLSI) technology that make high-speed, large-size fast Fourier transform (FFT) chips commercially viable [44].

The OFDM transmission scheme has the following key advantages [40]:

- OFDM is an efficient way to deal with multipath; for a given delay spread, the implementation complexity is significantly lower than that of a single carrier system with an equalizer.

- In relatively slow time-varying channels, it is possible to significantly enhance the capacity by adapting the data rate per sub-carrier according to the signal-to-noise ratio of that sub-carrier.

- OFDM is robust against narrowband interference, because such interference affects only a small percentage of the sub-carriers.

- Unlike other competing broadband access technologies, OFDM does not require contiguous bandwidth for operation.

- OFDM makes single-frequency networks possible, which is particularly attractive for broadcasting applications.

Over the past decade OFDM has been exploited for wideband data communications over mobile radio FM channels, high-bit-rate digital subscriber lines (HDSL) up to 1.6 Mb/s, asymmetric digital subscriber lines (ADSL) up to 6 Mb/s, very-high-speed subscriber lines (VDSL) up to 100 Mb/s, and an IEEE standard 802.11 (Wi-Fi) up to 54 Mb/s. Furthermore, OFDM is used in both fixed and mobile WiMAX technologies on a physical layer air interface for providing data rate ranging up to 120 Mb/s [43].

2.5. Optical networks

Optical networks are lightwave systems that use high frequencies (100 THz) in the visible or near-infrared region of the electromagnetic spectrum, and employ optical fibres for data transmission [3-5], [45]. A basic optical communication system has three basic components, transmitter, transmission medium (optical fibre), and receiver as shown in Figure 2.8. The transmitter consists of a light source (laser or LED) that can be modulated according to an electrical input signal to produce a beam of light, which is transmitted into the optical fibre. Typically the binary information sequence is converted into a sequence of on/off light pulses, which are then transmitted into the optical fibre medium. At the receiver, the on/off light pulses are converted back to an electrical signal by an optical detector. Since an optical network uses optical fibres for data transmission; it is more secure than other data transmission systems e.g., satellites, which suffer from satellite tapping (as light does not radiate from the fibre, it is nearly impossible to tap into it without detection). It is also immune to interference and crosstalk. The optical fibre also has potentially limitless capability, huge bandwidth (nearly 50 terabits per second) (Tb/s), low signal loss (as low as 0.2 dB/km, low signal distortion, lower power requirement, low material usage, small space requirement and security.

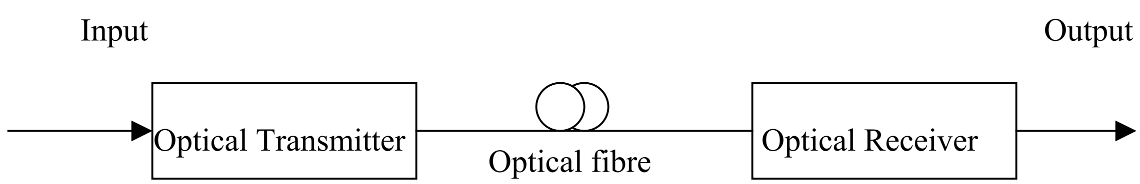

Figure 2.8: A basic optical communication system

The firstly generations of optical network became available in 1970 [3]. These optical networks used multimode fibres along with light-emitting diodes (LEDs) in the 0.8 μm wavelength region. The LEDs are relatively low power devices that emitted light over a fairly wide spectrum of several nanometers (nm) to tens of nanometers, thus, the bit rate was limited at 45 Mb/s with regenerators every 10 km [3], [4]. This led to a worldwide effort for the development of laser transmitters in a 1.3 μm wavelength region, but still the bit rates were limited to 140 Mb/s due to the dispersion, which occurred in multimode fibres. In 1984, the dispersion limitation was overcome by the use of single mode fibres.

Hence these optical networks (i.e. SONET/SDH) started to operate in the wavelength region of 1.3 μm with a bit rate of up to hundreds of megabits per second with a regenerator spaced every 50 km due to the use of standard single mode fibres (SSMFs). The above regenerator distance was limited at the operating wavelength region of 1.3 μm due to the attenuation loss of 0.5 dB/km in the standard single mode fibre. To overcome this issue, they operated at in the wavelength region of 1.5 μm that had a lower loss of 0.2 dB/km in the standard single mode fibre (SSMF) [4]. This enabled a longer distance between regenerators, however, another system impairment called chromatic dispersion started to become a limiting factor in this wavelength region in the standard single mode fibre. The chromatic dispersion impairment motivated the development of dispersion-shifted fibre, but at that time there was already a large installed base of the standard single mode fibre deployed for which this solution could not be applied [4]. For this reason, researchers had to find the ways to overcome chromatic dispersion in standard single mode fibre. This led to the development of a single-longitudinal mode (SLM) laser (i.e. Distributed feedback laser- DFB) [4]. An SLM laser emits a narrow single wavelength signal in a single spectral line. This optical technology breakthrough spurred further increases in the bit rate to more than 1 Gb/s. A drawback of this optical network technology is that the signal is to be regenerated every 60-70 km distance, which is very expensive due the high cost of regenerators. The first generation of optical network technology is called SONET (synchronous optical network in America) and SDH (synchronous digital hierarchy network in Europe) [3-5], [45].

The second generation of optical network technology was called the wavelength division-multiplexing (WDM) network [3-5], [45]. This optical network technology was achieved after the development of erbium-doped fibre amplifiers (EDFAs) for increasing the regenerator spacing. A major advantage of EDFAs is that they are capable of amplifying signals at many wavelengths simultaneously. This provided another way of increasing the system capacity: rather than increasing the bit rate, keep the bit rate the same and use more than one wavelength to transmit a bit rate. The use of WDM and EDFAs dramatically brought down the cost of ICT infrastructure and increased their capacity. At each regenerator location, a single optical amplifier replaces an entire array of expensive regenerators, one per fibre. This proved to be so compelling that almost every ICT backbone infrastructure in developed countries has been deployed with the use of WDM networks today. Optical WDM networks were deployed starting in the mid-1990s and are today achieving capacities over 1 Tb/s over a standard single mode fibre. However, nowadays these networks are renamed as dense wavelength division multiplexing (DWDM) [3-5], [45]. The following sections describe briefly the SONET/SDH and DWDM networks.

2.5.1. SONET/SDH networks

SONET is the optical network technology used to transmit high-speed data streams in North America. A similar standard to SONET but which has been adopted in Europe, Japan and in developing countries is called SDH. SONET/SDH employ a TDM multiplexing scheme, which can be easily implemented in today's very large-scale integrated (VLSI) circuits. All equipment in SONET/SDH is synchronised to a single master clock. The basic transmission rate defined in the SDH [4] is 155.52 Mb/s abbreviated to 155 Mb/s and is known as a synchronous transport module level 1 signal or simply STM-1. Higher rates of STM-4 (622 Mb/s), STM-16 (2.4 Gb/s), STM-64 (10 Gb/s), STM-256 (40 Gb/s) are also defined by ITU-T [4]. In SONET the lower rate of 51.84 Mb/s forms the first level signal STS-1. SONET hierarchy uses the term synchronous transport signal (STS) to define the equivalent of an STM signal (Note that an STS is an electrical signal). The optical interfaces corresponding to the STS-1 rate is called OC-1 (optical carrier-1), and similar optical interface have been defined for OC-3, OC-12, OC-48, OC-192, and OC-768 corresponding to the STS-3, STS-12, STS-48, STS-192, and STS-768 signals. The SDH and SONET data rates are compatible; an STM-1 data stream is equivalent to an STS-3/OC-3 stream. A summary of SONET and SDH data rates are shown in Table 2.1. In SONET/SDH, Multiplexing multiple STM-1 (STS-3/OC-3) signals together produces the higher-order transmission rates. For example, multiplexing either 16 STM-1 (STS-3/OC-3) or 4 STM-4 (STS-12/OC-12) signals produces an STM-16 (STS-

48/OC-48) signal. The STM-1 (STS-3/OC-3) signal is comprised of repetitive set frames that repeat with a period of 125 microseconds. The information content of each frame can be used to carry multiples of 1.5/2/6/34/45 or 140 Mb/s data stream.

A SONET/SDH frame consists of some overhead bytes called the transport overhead and the payload bytes. The payload data is carried in the so-called synchronous payload envelope (SPE). The SPE includes a set of additional path overhead bytes that are inserted at the source node and remain with the data until it reaches its destination node. SONET/SDH makes also extensive use of pointers to indicate the location of multiplexed payload data within a frame. The SPE doesn't have a fixed starting point within a frame. Instead, a pointer in the line overhead indicates its starting point. A detailed discussion about frame structure in the SONET/SDH network is beyond the scope of this research, for more information see [4].

SONET Signal	SDH Signal	Bit Rate (Mb/s)
STS-1		51.84
STS-3	STM-1	155.52
STS-12	STM-4	622.08
STS-24		1244.16
STS-48	STM-16	2488.32
STS-192	STM-64	9953.28
STS-768	STM-256	39,814.32

Table 2.1: SONET/SDH data rates [4]

2.5.2. Optical DWDM networks

In the first generation, optical network technology (i.e. SONET/SDH) as discussed above was essentially used for transmission and simply to provide capacity. SONET/SDH provided lower bit error rates and higher capacities than copper cable technologies. In SONET/SDH, all the switching and other intelligent network functions are handled by electronics. The second-generation of optical network technology (i.e. WDM/DWDM) incorporates the routing and switching functions into the optical layer [4]; hence it provides the required bandwidth and flexibility to enable end-to-end wavelength services. Optical networks began with wavelength division multiplexing (WDM), which arose to provide additional capacity on SONET/SDH networks. The term WDM was once used to signify the use of 2 wavelengths per fibre; nowadays the term DWDM is used to refer more than hundred wavelength channels per fibre [3-5], [45]. DWDM provides virtual fibres, in the sense that it makes a single fibre look like multiple “virtual” fibres, with each virtual fibre carrying a wavelength channel. A DWDM network multiplexes many wavelength channels and is capable of providing data capacity in excess of hundreds of gigabits per second over thousands of kilometers in a single mode fibre. In current high-end DWDM networks optimised for core networking, each wavelength (or channel) can operate at more than 40 Gb/s [46-49]. The DWDM network can support more than 100 wavelengths per fibre, thus enabling a single fibre to carry several hundred gigabits of information. DWDM networks supporting terabits per fibre have been demonstrated in laboratories and have been promised for future commercial deployment [50-52].

Various DWDM network topologies are possible ranging from simple point-to-point networks to dynamic wavelength routed networks (i.e. ring topology), as shown in Figure 2.9 and 2.10 respectively. Optical DWDM networks provide lightpaths to its users, such as SONET/SDH terminals or IP routers. Lightpaths are optical connections carried end to end from a source node to a destination node over a wavelength on each intermediate link. At intermediate nodes in the network, the lightpaths are routed and switched from one link to another link. For that reason, different lightpaths in a wavelength routed DWDM network can use the same wavelength as long as they do not share any common links [4-5]. The key network elements that enable optical DWDM networks are Optical line terminals (OLTs) (which constitutes transmitters, receivers and MUX/DEMUX), Reconfigurable optical add/drop multiplexers (ROADMs), and optical crossconnects (OXC).

An OLT multiplexes multiple wavelengths into a single fibre and demultiplexes a set of wavelengths on a single fibre into separate fibres. OLTs are used at the ends of a point-to-point DWDM network as shown in Figure 2.9. While ROADM/OXC takes in signals at multiple wavelengths and selectively drops some of these wavelengths locally while letting others pass through. ROADM/OXC is used in the DWDM routed networks as shown in Figure 2.10.

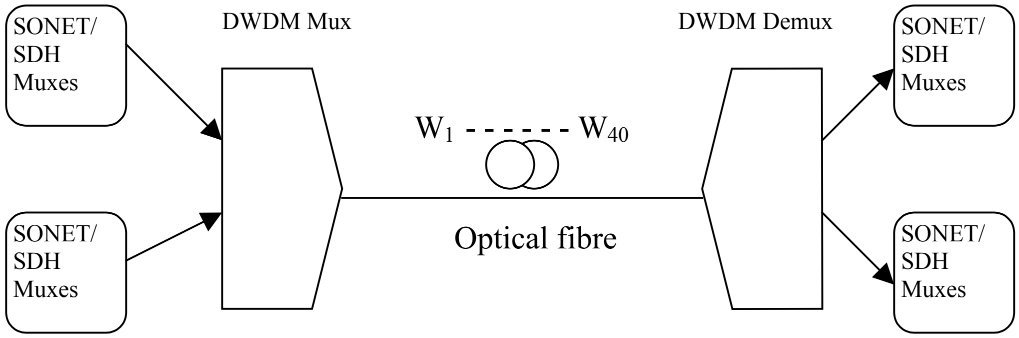

Figure 2.9: Point-to-point optical DWDM network (40-wavelength channels)

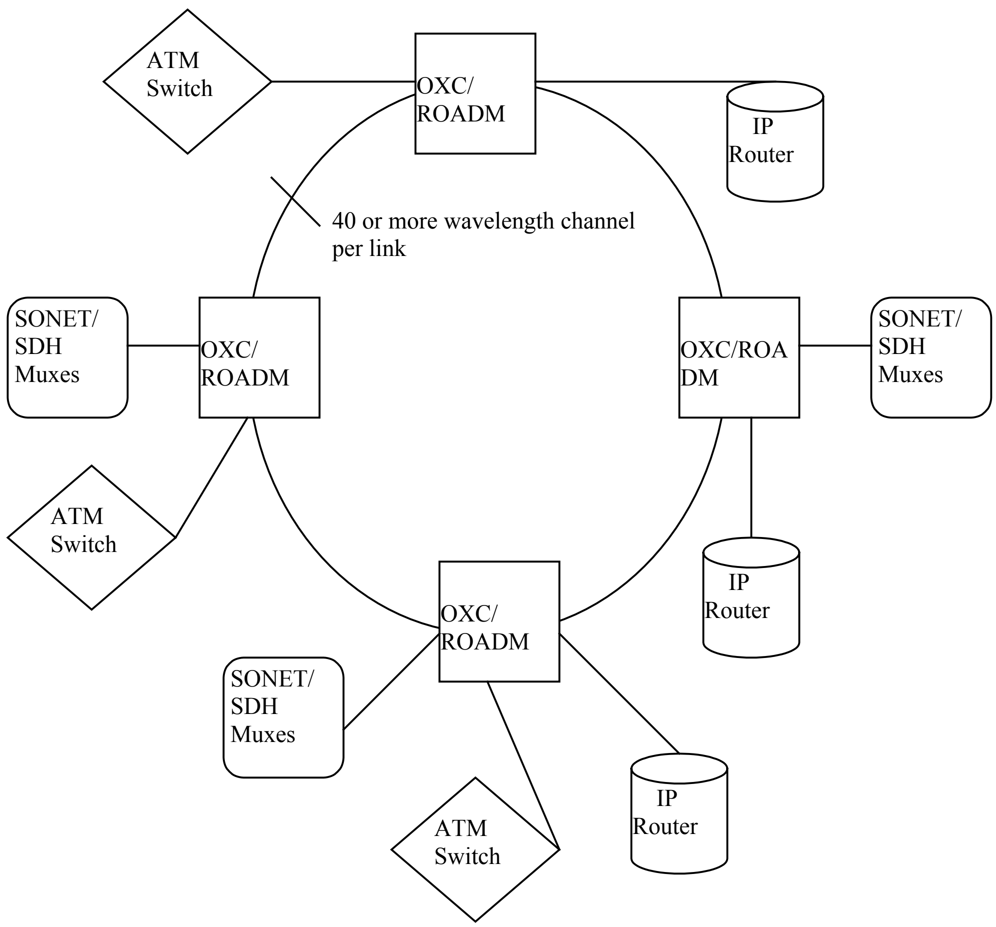

Figure 2.10: A ring DWDM routed network

2.6. Conclusion

In this chapter, we have seen that PSTN/PDSN and a wireless based network technology (WiMAX) are mostly used as metro or access networks; they can't be used as an ICT backbone infrastructure due to bandwidth limitations. Satellites can be used as a backbone but they are affected by moisture and rain, and also a clear line of sight between VSAT and the satellite is required. Furthermore, it is very expensive to use a Satellite communication system to provide high bandwidth for backbone purposes. The explosive growth of the Internet and bandwidth intensive applications such as video-on-demand (for example, selecting a movie located at some remote site and watching it online) and multimedia conferencing (which requires setting up high bandwidth connections among different users, for virtual meeting, and guaranteeing the desired quality-of-service (QoS) levels, low latency, and reasonable packet loss rate for the virtual meeting) require high speed ICT backbone infrastructure such as an optical network to provide high bandwidth. We have seen that optical network technology has evolved over the past few decades to offer higher data rates on an optical fibre over longer distances. For example, first-generation optical networks (i.e. SONET/SDH) used optical fibre as a replacement for copper cable to get higher capacities. While, a second-generation of optical network technology (i.e. DWDM networks) incorporates the routing and switching functions into the optical layer that were performed by electronics in SONET/SDH networks; hence it provides enormous bandwidth with minimum costs compared to SONET/SDH networks. For example, as data rates get higher and higher, it becomes more difficult for SONET/SDH networks to process data in electronic form. Suppose the networks must process data in blocks of 53 bytes each (i.e. the block size in ATM networks). In a 100 Mb/s data stream, 4.24 μs is required to process a block, whereas at 10 Gb/s the same block must be processed within 42.4 ns. In a SONET/SDH network the electronics at a node must handle not only the data intended for that nodes but also all the data that is being passed through that node on to other nodes in the network. If that data were routed through in the optical domain (i.e. by the use of DWDM networks), the burden on the underlying electronics at the node would be significantly reduced. This is one of the key advantages of the second-generation optical networks (i.e. DWDM network). A DWDM network provides many benefits such as scalability capacity, transparency, and survivability. In this regard, DWDM networks have gained strong favor for ICT backbone infrastructure solutions and are capable of delivering high bandwidth in a flexible manner where and when needed rather than other telecommunication network technology. Many studies have confirmed the cost-effectiveness of DWDM networks, which due to high demand has decreased the cost of optical components [53-57].

CHAPTER 3: ICT SURVEY FOR TANZANIA

3.1. Introduction

Tanzania is a union of two countries namely, Tanganyika (Tanzania mainland) and Zanzibar islands (Unguja & Pemba). Tanganyika became independent from United Kingdom in 1961 through a political party called Tanganyika African national union (TANU), which was led by the late political leader and a national father, Julius Kambarage Nyerere. Zanzibar islands achieved their independence through the Afro Shiraz party later in 1963, which was lead by the late vice president Abeid Karume. In 1964, the union between Tanganyika and Zanzibar formed the united republic of Tanzania. Tanzania is located in East Africa, sharing a border with Kenya and Uganda (North), Rwanda, Burundi, Republic of Congo (West), Zambia, Malawi, Mozambique (South) and the Indian Ocean (East) (Figure 3.1). The country covers an area of 945,087 km^2 (942,430 km^2 for the mainland and 2657 km^2 for the islands). In 2009, the total population of Tanzania was estimated to be approximately 41 Million [58]. The majority of Tanzanians (75%) dwell in rural areas while only 25% live in urban areas. For this reason, it remains one of the least urbanised African countries.

The country has 25 cities (Mainland 20 and Islands 5) and 114 Districts. The 25 regions are Arusha, Coast, Dodoma, Iringa, Kigoma, Mbeya, Mara, Kilimanjaro, Morogoro, Mtwara, Mwanza, Lindi, Ruvuma, Shinyanga, Singida, Tabora, Tanga, Kagera, Rukwa, Dar es Salaam, Zanzibar Town/West, Zanzibar North, Zanzibar South, Pemba North, and Pemba South. Between 1967 and 1990 Tanzania followed a socialist economic philosophy. As result a large parastatal sector was built up to carry out activities in the sectors of industry, agriculture, transport and communications, mining, education, health, fisheries etc. But starting in 1991, Tanzania started to follow a free market, capitalist philosophy. The government started to divert itself to production parastatals and encouraged private sector participation in the economy.

However until now, the Tanzanian economy is still largely driven by the agricultural sector, manufacturing, ICT, Mining and Tourisms are small, but rapidly growing economic sectors. In 2000, agriculture accounted for nearly two thirds of GDP and over 80% of the workforce and exports earnings (predominantly crops, fishing and livestock). In 2003, the

figures were estimated as follows: agricultural 43.6%, industry 16.5% and services 40%, indicating that the economy has become more broadly based from both sectors [59].
In 2008, investment performance was increasing with a marked increase in the number of capital projects in Dar es Salaam and other cities. For example, manufacturing contributed less than 10% to GDP, but growth was still high in comparison to other sectors; this is mainly due to a rapid program of privatisation of state assets under the direction of the 'Parastatal Sector Reform Commission' (PSRC) [60].

Despite the economic and development challenges, Tanzania is still one of the most politically stable African countries. For about the past thirty years, one political party, Chama Cha Mapinduzi (CCM) has ruled Tanzania. However, Tanzania adopted a multi-party political system in 1992. The first multi-party parliamentary and presidential elections were held in October 1995. Economic and Political liberalisation has gone hand in hand with the liberalisation of policies governing the news media. Tanzania has gone from a state where all news media were government controlled to a state where there is a vibrant private press, private radio station and private broadcasting companies.

Figure 3.1: A map of Tanzania

3.2. History of Tanzanian Telecommunications

The evolution of telecommunications in Tanzania can be traced back to the early 1920s, when the then Tanganyika and Zanzibar were still under the colonial rule of the United Kingdom. By then, postal and telecommunications infrastructure spread across the country based on the colonial settlement locations. The merger of the three independent Postal, Telegraph and Telephone networks in the then Tanganyika, Kenya and Uganda took place in 1933, which resulted in the formation of a company known as the East African Posts and Telegraph Company. In 1951, the East African Posts and Telecommunication provided and covered all postal and Telecommunications services, which later on came to be known as the East African Posts and Telecommunications administration.

In 1961, when Tanganyika became independent, the East African high commission gave way to a new organisation, the East African common service organisation (EASCO), headed by a postmaster general (PMG). In 1964 Tanganyika united with the Islands of Zanzibar, which formed the united republic of Tanzania. It resulted on 1st December 1967 in the establishment of the East African community, which became operative from 1st January 1968 replacing the then East African Common services organisation. It also brought certain changes in the operation of Post & telecommunication administration. The name was changed from administration to corporation, and therefore the organisation East African Posts and Telecommunications Corporation (EAP & TC) was formed. Following the disintegration of the East African Community in 1977, Tanzania formed the Tanzania Posts and Telecommunication Corporation (TP&TC).

3.3. Liberalisation of Tanzanian Telecommunication

Until 1993, TP&TC had a monopoly in provision of telecommunications and postal services. In addition, it was also the regulator of all telecommunication sectors, including radio frequency spectrum management. However later in 1993, the telecommunication sector was liberalised, and private companies were allowed to distribute and supply telecommunication services in Tanzania. In 1994, a decision was made to restructure the telecommunications sector in order to extend the coverage, improve the quality of local and international telecommunication and postal services. This led to dissolution of

TP&TC, and the establishments of Tanzania Telecommunication Company Limited (TTCL) [61], Tanzania postal services (TPC), and Tanzania Communications Commission (TCC). The TCC was responsible for regulation of the telecommunication and postal services, and other functions as follows:

- Licensing telecommunications and postal operators, equipment vendors and contractors, and monitoring their performance;
- Allocating and managing the radio frequency spectrum;
- Type approval and standardisation of telecommunication equipment;
- Regulating telecommunication and postal tariffs;
- Promotion of the telecommunication and postal services in accordance with recognised International standard practices and public demand;
- Establishment of standards and codes relating to equipment attached to telecommunication systems;
- Promote and encourage the expansion of telecommunication and postal services with a view to the economic development of Tanzania;
- Acts as international representative of Tanzania in respect to telecommunication and postal matters;
- Law and policy enforcement;
- Arbitration of disputes between operators and between operators and customers;
- Promoting competition in the postal and telecommunication industries; and

- Monitoring the quality of postal and telecommunication services.

3.3.1. Tanzania Communications Regulatory Authority (TCRA)

During the last twenty years there has been a global transformation in telecommunications; technological innovation, new regulatory and new license frameworks, market structures, and proliferation of telecommunications services have caused profound changes in the telecommunication sector, which have contributed to global economic development. Responding to this, Tanzania launched a national telecommunication policy [62] in order to accelerate development of an efficient telecommunication infrastructure that could provide telecommunication services and international connections for all economic sectors and the majority of the population. As well as to optimize its contribution to the development of the Tanzanian economy as a whole by ensuring the availability of efficient, reliable and affordable telecommunication services throughout the country. However, no initiatives were taken to implement this policy until the establishment of TCRA [63] in 2003. The TCRA was established through the convergence of TCC and the Tanzania Broadcasting Commission.

The TCRA mission was to enhance the welfare of Tanzania through the following [64]:

- Promotion of effective competition and economic efficiency
- Protecting the interests of consumers
- Promoting the availability of regulated services
- Licensing and enforcing license conditions of broadcasting, postal and Telecommunications operators
- Establishing standards for regulated goods and services
- Regulating rates and charges (Tariffs)

- Managing the radio frequency spectrum

- Monitoring the performance of the regulated sectors, and

- Monitoring of the implementation of ICT services applications.

But in contrast to its mission, TCRA was still facilitating the old regulatory license framework of TCC until the establishment of the ICT sector, which took place the same year (2003) but later on. The old regulatory license framework had the following limitations [64]:

- It was not flexible enough to match the dynamism of the telecommunication sector

- It was limited by the exclusivity of everything being given to the government owned company, TTCL.

- Internet service providers were prohibited from providing some services such as the VOIP services, which could be cheaper to consumers.

3.4. Establishment of an ICT Sector

The information communication and technology (ICT) sector was formed through the merger of the telecommunication and information technologies sectors in 2003. The mission of the ICT sector was to provide more affordable access to a range of ICT services to as many people as possible so as to enhance sustainable socio-economic development and to participate in the global networked economy. Also, the establishment of ICT caused a necessary change of the old license framework, which had been in place since telecommunication liberalisation in Tanzania. The new license framework [64] goal was to provide more affordable access to a range of ICT services, from voice to high-speed Internet access to the majority of the people who can afford it. The old license framework wasn't flexible enough to couple with the ICT sector due to facilitating the monopoly of the Tanzania Telecommunication Company limited (TTCL), which was owned by the government. Also, Data operators and ISPs were prohibited from providing Voice over IP (VOIP) services. In contrast to the national ICT policy [15] whose objectives were to encourage competition in the ICT sector so as to facilitate Tanzanians with a choice of high-functionality and affordable services, attract inward investments and enable the country to act as a regional and international hub for ICT traffic and services. But, these objectives could not be achieved due to limitations in the old license framework. As a result, it was decided that there was a need to move from the old license framework to a new license framework, which was expected to address some of the bottlenecks and challenges in the ICT sector.

The new license framework was set up to address the following [64], [65]:

- Promotion of competitiveness in order to ensure that the transition to converged licensing fosters a level playing field among all operators.

- Simplifying existing licensing procedures in order to ease market entry, operations, applications and services. This would enable more players to participate in the industry.

- Bridging the digital-divide between rural and urban areas by introducing district licenses supported by rural communications development funds.

- Adopting regulatory flexibility to address market and technological developments

- Enforcement of efficient utilisation of network resources and creating more employment.

3.4.1. New License framework

In a new license framework the government planned to achieve a technology neutral and service neutral framework through the following four main categories of licenses [64], [65]:

3.4.1.1. Network facility (NF)

This license authorised owner construction and ownership of electronic communication network infrastructure such as Earth Stations, Fixed links and cables, Public Payphone facilities, Radio communications transmitters and links, Satellite hubs, Satellite control station, Space station, Submarine cable landing centre, Switching centre, Tower, poles, ducts and pits used in conjunction with other network facilities.

3.4.1.2. Network service (NS)

This license authorised the owner to operate electronic communication networks such as network services, Bandwidth services, Broadcasting distribution services, Cellular mobile services, Access applications service and Space Segment Services.

3.4.1.3. Application service (AS)

This license authorised the reselling or procurement of services from Network Service operators.

3.4.1.4. Content application service (CAS)

This license authorised the provision of services such as Satellite broadcasting, Broadcasting Terrestrial free to air TV, Terrestrial radio broadcasting and other electronic media.

3.4.2. ICT service operators

In Tanzania, ICT service operators are classified into the following groups: Basic Telephone Operators; Mobile Operators; Public and Private Data Operators; Internet Service Providers; Broadcasting Stations; Postal and Courier Operators; Contractors [64], [65]. Currently, two companies have been granted licenses to provide basic telephony and international gateway services. These are TTCL in the mainland and Zantel in the Zanzibar islands. The TTCL however had a monopoly license from 2001 until 2005 to provide the basic telephony services and international gateway connections for all operators on the mainland. There are twenty-one licensed Internet Service Providers providing Internet services and four mobile operators (Mobitel, Celtel, Vodacom, and Zantel).

3.5. ICT Policy

The economy in Tanzania depends heavily on agriculture, tourism and minerals. In order to develop its economy and close the digital divide between the global information communities, the National ICT policy was launched in 2003 [15]. The ICT policy objectives were based on vision 2025 that envisages a nation imbued with five main attributes: high quality livelihood; peace, stability and unity; good governance; a well educated and learning society; and a strong and competitive economy capable of producing sustainable growth and shared benefits [15]. This policy has articulated ten main focus areas in harnessing ICT in Tanzania which include strategic ICT leadership; ICT network; ICT industry; Human capital; Legal and regulatory framework; Productive sectors; service sectors; Public service; Local content; and Universal access. The vision of the national ICT policy is for “Tanzania to become a hub of ICT infrastructure and ICT solutions that enhance sustainable socio-economic development and accelerated poverty reduction both nationally and globally” [15].

The overall mission of this policy is to enhance nation-wide economic growth and social progress by encouraging beneficial ICT activities in all sectors through providing and in promoting multi-layered co-operation and knowledge sharing locally as well as globally. The establishment of TCRA and formation of ICT policy missions were to facilitate the new licensing procedures for easy market entry, operator opportunity, new applications and ICT services. To bridge the digital-divide between rural and urban areas by introducing district licenses supported by rural communications development; and enforcement of efficient utilisation of network resources to create more employment. Also to facilitate Tanzania to join the group of countries with an integrated infrastructure for ICT services.

3.6. Status of ICT services in Tanzania

Reliable ICT services reduce the influence of geographical obstacles in bringing people together, and improve the productivity and efficiency of agriculture, industry, social services. It enhances socio-economic development to produce better living conditions in any country. Despite the establishment of TCRA, formation of ICT policy, and adaptation of the new license framework most people in Tanzania have no access to ICT services because the country doesn’t have an internationally connected terrestrial ICT backbone infrastructure. The vast majority of ICT services in Tanzania are located in urban areas of major cities. This creates a digital divide within the country, and also with other countries. For example, in developed countries there are on average, 50 fixed telephone lines (landlines) per 100 people [66], but in Tanzania there are approximately 0.5 fixed telephone lines per 100 people [66]. The statistics published by [66] on global use of the Internet, show that Tanzania has the same inequality in Internet connections.

In order to understand the status of ICT services in Tanzania (sections 3.6.1-3.6.11), and existing ICT infrastructure (section 3.7); Chief executives, senior management staff, ICT professionals, sales and marketing officers in Tanzania were interviewed across a range of public and private organisations, and also several visits were made to various Internet cafes in the country.

3.6.1. Internet Services

Internet services in Tanzania have been available since 1996, however until 2009 the Internet penetration was approximately 1.3% [67], this is due to the lack of an ICT backbone infrastructure. The major concentration of Internet services is found in the urban areas of the commercial city, Dar-Es-Salaam and other major cities, e.g. Arusha, Mwanza, Dodoma and Morogoro. The majority of the people who live in rural areas do not have Internet access, and those who live in urban areas depend on expensive low speed satellite connections. For example, the monthly charge for a residential Internet bandwidth of 64 Kb/s and a commercial Internet bandwidth of 512 kb/s are approximately $60 and $800 (USD) [68], respectively. Most people who are employed and students can’t afford Internet access at home; they can only access it in the workplace and in Universities. Other people access the Internet through Internet cafes at a cost ranging from $0.5 to $1 per hour. Most Internet cafés in Tanzania are in urban areas. Internet penetration in rural areas is very low because of the high cost of satellite connections.

3.6.2. E-commerce

In the financial sector Internet services have increased slightly for tax revenue collection and administration department, which is managed by the Tanzanian revenue authority (TRA) company. Since the introduction of ICT the TRA has managed to increase tax collection from about 10% of the Gross domestic product (GDP) in 1996 to about 14% by 2005 [69]. Most of the TRA forms e.g. customs and excise, VAT, domestic revenues and etc, are available online. Also, the management of transactions for transit goods is through regional networks (i.e. metros) connected by the use of the public switched circuit network (PSTN), very small aperture terminal (VSAT) and microwave links. However, these networks are only located in major cities e.g. in DSM, Tanga, Arusha, Moshi, Dodoma, Mbeya and Mwanza. The project to connect all TRA regional offices across the country was introduced in 2002/2003, however it is not yet implemented in all TRA regional offices.

3.6.3. E-banking

The major user of E-banking in Tanzania is by the bank of Tanzania (BOT), a government bank. BOT has a local area network (LAN) of over 750 personal computers connected via VSAT in its head offices in Dar-es-salaam; this is used for transactions with electronic funds, smart cards and other online applications to other banks in Tanzania or in other countries [69].

There are only a few ATM cash machines from different banks in the country that are connected by VSAT that provides cash transactions compared to other developing countries. Small banks can't afford to install ATM machines due to the high cost of the VSAT connection. Also at the moment there are few banks that provide Internet banking to their customers.

3.6.4. E-education

Researchers and students in Universities still find difficulty in accessing electronic journals or course material from abroad through the Internet because of the slow speed of the Internet connection. For example, the University of Dar-es-salaam (UDSM) has a local area network (LAN) connected with an optical fibre network, which is connected internationally through satellite links via the VSAT connection. Yet students or researchers can't download files from the Internet due to the low speed of the Internet connections. The university of Dar-es-Salaam and the other three academic institutions e.g. Sokoine University, Institute of Finance management (IFM), and Dar-es-salaam Institute of Technology (DIT) are the only ones in Tanzania with an Internet connection speed in excess of 256 Kb/s through their VSAT connection; other institutions still depend on a Dial up Internet connection of 56 Kb/s. Though currently there are some projects supported by international organisations to improve ICT in the education sectors in Tanzania for example Tanzanian education network (TENET) [70], however it is unknown when this project will finish.

3.6.5. E-governance

E-governance is one of the areas that would benefit greatly from ICT development, Tanzania lags behind other countries in taking advantage of this opportunity. Currently, there are a few regional government offices in the commercial city of Dar-es-Salaam, which are connected with VSAT and microwave links [69]. However, efforts are underway to link all ministries, regional and local government offices in each city in Tanzania, but it is still not known when they will be successfully connected.

3.6.6. E-health

A Swedish International Development Agency (SIDA) project presently provides tele-medicine by linking dispensaries and health centres in some rural areas of Tanzania [71]. The Professor Hubert Kairuki Memorial Hospital (a private hospital) also provides a tele-medicine system between its main hospital office and its city centre branch (about 10kms apart in Dar-es-Salaam) by the use of a VSAT connection [69]. Also, at the moment there is another tele-medicine project, which is supported by the Evangelical Lutheran church in Tanzania (ELCT) [72]. The ELCT connects 20 hospitals, 5 paramedical centres and 160 dispensaries in different cities and districts in Tanzania using a VSAT connection; as a result it contributes nearly 15 percent of E-health services in Tanzania. However, Tanzania still needs more tele-medicine services especially in rural areas due to the shortage of medical doctors.

3.6.7. E-marketing

Some firms in Tanzania, both small and large reap benefits from advertising on the Internet. For example some companies have setup websites presenting company profiles, product/service catalogues and a communication line via e-mail. Also the growth in the tourist industry has been facilitated through e-marketing, tourists use websites to find out where to go before making detailed plans. Handicrafts and art are other lines of business that are advertised through the Internet [69].

3.6.8. Telecentres

Telecentres are alternative solutions for those lacking mobiles or landlines to communicate via public telephone boxes. Currently, there are ongoing projects supported by SIDA [71] and the International Institute for Communication and Development (IICD) [72], through the Tanzanian government, to develop community telecentres in most remote rural areas, this exploits VSAT and microwave links.

3.6.9. Fixed telephone lines

The fixed telephone line services have been upgraded from an analogue public switched circuit network (PSTN) to an integrated switched digital network (ISDN) in urban areas of major cities. Also, there is a microwave (wireless) backbone network that connects Dar-es-salaam, Zanzibar, Pemba, Tanga, Moshi and Arusha. A wireless local area network (WLAN) covers a few urban areas in Tanzania. When the PSTN was upgraded to ISDN in major cities in 2000, the total fixed telephone line subscribers were 173,591 (see table 2). It was predicted that the total numbers of fixed telephone lines subscribers would grow but until late 2008, the total fixed telephone lines subscribers decreased to 163,300 (see table 2), this is due to the competitive market from mobile phone networks, which had only 126,646 subscribers in 2000 but had increased to 11.6 million subscribers in late 2008, as shown in table 3.1.

Year	Fixed Lines	Mobile	Total
2000	173,591	126,646	300,237
2001	177,802	275,560	453,362
2002	161,590	606,859	768,449
2003	147,006	1,295,000	1,442,006
2004	148,360	1,942,000	2,090,360
2005	154,420	3,389,787	3,544,207
2006	157,287	5,609,279	5,766,566
2007	163,269	8,322,857	8,486,126
2008	**163,300**	**11,556,329**	**11,719,629**

Table 3.1: Fixed lines and mobile phones subscribers [73]

3.6.10. Mobile phone subscribers

The growth in the number of Mobile network subscribers has been dramatic in recent years with most mobile phone networks offering customers pre and post paid systems. There are currently seven mobile networks operating in Tanzania, giving coverage to almost all locations in the country. At present, there are more than 11 million mobile network subscribers [73]. Several mobile network operators have already launched Internet services over the mobile phone network using 3G (the third generation of mobile network) technologies. Mobile phones are the only ICT services, which have good market penetration in rural areas.

3.6.11. Multimedia

Multimedia industries in Tanzania operate on free market principles. Private individuals are allowed to own television and radio stations. By the of end 2007, there were 28 private broadcasting stations, one national broadcasting station, 47 private radio stations and only one national radio station [73]. Since 2008, a national broadcasting station called Tanzanian broadcasting company (TBC) had started a project to build towers for television broadcasting with the intention of providing coverage to the majority of the people who live in rural areas. Once this project finishes, it is expected to raise the number of people accessing television services, even in the rural areas.

3.7. Existing ICT infrastructures in Tanzania

ICT service providers in the country are still dependent on the PSTN/PSDN, VSAT and microwave networks to deliver ICT services to their customers, with Satellite links providing the international connection. In the past, all customers were receiving only dial up Internet services with a 56 kb/s data rate, but when the PSTN was upgraded into PSDN in some urban areas, the Internet services improved slightly in those areas; for example: Internet users have been receiving Internet residential bandwidth of 64 to128 kb/s instead of a dial-up service, though the cost is very high [68]. Most commercial Internet users have VSAT dishes for Internet connection.

The Tanzania Telecommunications Company Limited (TTCL) is the one of largest ICT service providers with a high bandwidth of 104 Mb/s downlink and 24 Mb/s uplink delivered through a satellite link from abroad via a hub located in Dar-es-salaam [74]. TTCL regional networks (metro) have the widest coverage in Tanzania with all urban areas in major cities and some districts covered by microwave, PSTN/PSDN and VSAT networks. The TTCL satellite hub is connected in a star configuration with its regional networks to deliver ICT services to the majority of the people who live in the urban areas of Tanzania.

Apart from TTCL, There are other ICT service providers who use microwave and VSAT links to provide ICT services to commercial Internet customers in urban areas. For example, Afsat [75] provides ICT services to specific customers especially in the banking sector by using VSAT networks. Another ICT service provider is SATCOM network Africa Limited [76]; it has its own satellite hub and covers the urban areas of the major cities in the country with a VSAT and microwave network to provide ICT services to its Internet customers.

Most VSAT dishes in Tanzania operate in the C band with circular polarization; this is to combat heavy rain that can cause disruption. Typically VSAT dish sizes range from 1.8m, 2.4m and 3.8m, which are very expensive for an individual to own. However there are few companies that use the Ku band which uses smaller VSAT dishes, these are less expensive.

For example, SimbaNET [77], another ICT service provider uses an advanced technology of high bandwidth digital video broadcast (DVB) with Ku band dishes to create multiple downlink points to some commercial Internet customers in urban areas.

Another existing ICT infrastructure belongs to the Tanzania people's defense force (TPDF), which has its own satellite hub that links all the army bases in the country with more than 1000 VSAT connections [69]. TPDF only use 5% of the overall bandwidth capacity available from the Satellite. For this reason the Tanzanian government has proposed that this infrastructure could be used to link all government ministries, cities and district local government offices, and all government hospitals across the country. This would greatly improve e-government; however the project has not yet started.
Also, there is a proposed government project to implement a national ICT backbone infrastructure [78] by using optical fibre and connect it to the rest of the world through South Africa by means of the East African Submarine System (EASSy) [79], but it is still not known when this project will finish.

3.8. Conclusions

This chapter presented an ICT survey for Tanzania that includes background information and an historic perspective of telecommunications in Tanzania. According to the ICT survey, it revealed how Tanzania lacks an internationally connected terrestrial ICT backbone infrastructure; since the Internet connection to the rest of the world is via expensive Satellite links through Europe or America. This has caused ICT service providers to operate with a high cost base that has slowed down their ability to penetrate the market, especially in rural areas where the majority of people live. For example, ICT service providers are paying more than $2 Million per annum (excluding operational, sales, marketing and administration costs, etc) to lease one commercial satellite transponder with a 34 Mb/s downlink [80]. As a result it is been difficult to lower Internet access costs in Tanzania.

As well as, it would be prohibitively expensive and operationally difficult for Tanzania to launch its own satellite communication system to connect all cities to meet the required bandwidth demand. For example to construct a satellite communication system to provide ICT services to the majority of the people who live in urban and rural areas for at least 10 years would cost the country more than $40 Billion [80].

The high cost of satellite connection has delayed the penetration of ICT services such as, Internet access, E-education, E-governance, E-banking, E-health, E-commerce, E-tourism, E-agriculture, E-manufacturing, telemedicine, etc to the majority of the people who live in urban and rural areas.

CHAPTER 4: ICT INFRASTRUCTURE CONCEPT FOR TANZANIA

4.1. Introduction

The chapter (3) has revealed that Tanzania lacks an internationally connected terrestrial ICT backbone infrastructure; since the Internet connection to the rest of the world is via expensive Satellite links through Europe or America. In most places around the world the ICT backbone infrastructures are supported by optical fibre technology, most notably dense wavelength division multiplexed (DWDM) networks. Optical DWDM networks can provide vast amounts of information for every resident and also provide access for schools, universities, hospitals and community centres [3-5], [45]. Innovations in ICT backbone infrastructures coupled with optical DWDM networks, have lowered the costs of providing ICT services to virtually any location, for example from an inner-city neighborhood to a rural village or to remote areas in other places of the world [81-87]. As a result, optical DWDM networks have revolutionised long distance data transport and have resulted in high capacity data highways, cost reductions, extremely low bit error rate, and operational simplification of the overall ICT backbone infrastructure [53-57], [88], [89]. For this reason, an optical DWDM network [90] is proposed in this research for the deployment of an internationally connected ICT backbone infrastructure in Tanzania so as to provide sufficient capacity to meet ICT service demand for Internet, voice (fixed and mobile phones), voice-over-IP (VOIP), video and multi-media for the majority of Tanzanian people who live in urban and rural areas, such a system will also reduce the Internet access costs. This will help close the digital divide with other countries and enhance sustainable socio-economic development and accelerate poverty reduction in the country.

This chapter explores the following: the deployment considerations for an ICT Infrastructure that exploits an optical DWDM network technology; its economic aspects and implementation; and the access networks, which are connected with metro networks onto the ICT backbone infrastructure to provide voice and Internet services to majority of Tanzanian people who live in both urban and rural areas.

4.2. Deployment consideration

As it is expensive to install new optical fibres in the ground, an ICT backbone infrastructure that exploits an optical DWDM network technology has been proposed in this research, which makes use of the standard single mode fibres (SSMF) in the existing optical networks, these are currently owned by private and government companies [90]. These standard single mode fibres nearly cover the whole of the country, and also penetrate into the rural areas as shown in Figure 4.1 below. The existing optical networks are built using Synchronous Optical Network (SONET)/ Synchronous Digital Hierarchy (SDH) in the form of rings or point-to-point links in other areas, operating with a maximum bandwidth of 622 Mb/s using a single wavelength channel on a standard single mode fibre (SSMF)(or G.652 according to the ITU standard).

The optical networks that use the SSMFs in Tanzania are separated and owned by the following companies; Tanzania Telecommunication company limited (TTCL), which is funded by the government and donors to improve voice and Internet services; Tanzania-Zambia railway authority (TAZARA) and Tanzania railway corporation (TRC) which link all their stations along the railway lines for signaling and monitoring of the railway lines; Tanzania electric supply company (TANESCO) and Songo Songo gas supply (SONGAS) company in Tanzania also link all their electricity generation power stations, transmission and distribution control centres and substation centres with voice communication services [78].

These existing optical networks (SONET/SDH) use a single wavelength of light on one SSMF. Thus to take advantage of the extra capacity available in SSMF, a dense wavelength multiplexing (DWDM) network is proposed for deployment as the ICT backbone infrastructure [90]. The DWDM network exploits the huge capacity more efficiently by maximizing the use of SSMFs in the existing optical networks (SONET/SDH) to meet Internet traffic demand in Tanzania. Thus, the possibility of using existing SSMFs more efficiently makes a DWDM network technology a very attractive commercial proposition. Also using a relatively low bit rate, e.g. 2.5 Gb/s per wavelength channel makes the DWDM network less vulnerable to system impairments such as chromatic dispersion, polarization-mode dispersion, and nonlinearity effects [91]; hence this reduces DWDM system costs. An optical DWDM network of 40-wavelength channels with 2.5 Gb/s on each channel using a SSMF is used in this research to deploy a cost effective internationally connected ICT backbone infrastructure that provides at least 100 Gb/s capacity to meet ICT services traffic demands for the majority of Tanzanian people who live both in urban and rural areas in Tanzania [90].

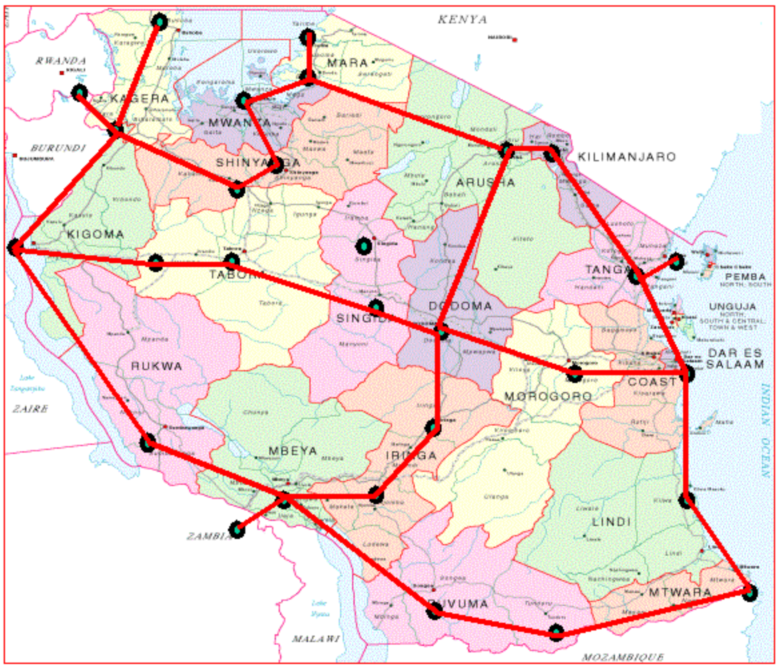

Figure 4.1: The existing standard single mode fibres in Tanzania (these fibres belong to different organisations and are not integrated DWDM systems)

4.3. Economic aspects of DWDM network

The development of DWDM networks has changed the economics of ICT infrastructure, for example, the optical cross-connect switch (OXC) is the DWDM network equipment that provides cross-connect functionality between input and output ports, each handling a bundle of multiplexed single-wavelength signals. By the use of OXC, the DWDM network offers a more scalable way to lower the costs of expanding capacity in the infrastructure [53]. OXCs make it possible to dynamically reconfigure optical DWDM networks at the wavelength level, this allows ICT service providers to transport and manage wavelength efficiently. This ability to dynamically reconfigure the DWDM network also makes it feasible to flexibly interconnect ICT services provided by multiple service operators, and thereby free some capacity from the ICT infrastructure needed to support secondary markets. Moreover, the DWDM Network provides great flexibility in building ICT backbone infrastructure, for example, if there is a network node through which most of the traffic has to pass and a small fraction is to be dropped and added, it is more cost-effective to use OXC or a reconfigurable add/drop multiplexer (ROADM) rather than terminate all the optical traffic and do the add/drop in the electronic domain (i.e. by the use of SONET/SDH network elements).

Since the DWDM network is based on wavelength routing, it allows the ICT service providers to assign separate wavelengths to different customers facilitating the provision of different ICT services over the same fibre [53]. Furthermore, as the incoming signals never terminate in the optical layer, the DWDM interface can be bit-rate and format independent, which allows the ICT service providers to easily integrate DWDM solutions with existing equipment in the network. Additionally, DWDM allows for a grow-as-you-go strategy, thus the ICT service providers can add higher-layer equipment such as SONET /SDH network elements (i.e. ADM), IP routers, ATM switches, etc on the top of a DWDM network, as needed, for a virtually endless capacity expansion. ICT service providers can also enjoy the flexibility to expand capacity in any portion of the ICT infrastructure, and address specific problem areas that are congested because of high bandwidth demand, which is usually the case where multiple rings intersect. Also the emergence of optical DWDM networks increases the need for secondary markets to facilitate the reallocation of available bandwidth.

The deployment of ICT infrastructure that unlocks a bandwidth restriction at one location can often create a bottleneck at another location because of the demand it satisfies. The uncertainties in demand sometimes are difficult to forecast accurately; how much bandwidth will be needed, at what time, and in which part of the network. Secondary markets allow the ICT service providers to transfer rights to use any available bandwidth in the dynamic optical DWDM network; this significantly reduces the ICT service cost to its customers. These additional benefits in terms of cost and performance make ICT backbone infrastructure built with DWDM networks more flexible and scalable than other telecommunication network technologies.

4.4. Implementation of Optical DWDM Network

Ring network topology has become very popular in the telecommunication system infrastructure community [4], [5], [92], [93]. A ring is the simplest network that provides two separate paths between any pair of nodes that do not have any nodes or links in common except the source and destination nodes. This allows a DWDM ring network to be resilient to failures, and also impose low network requirements on the optical hardware; network protection and on the network management system [4], [5], [82], [92-94]; hence it reduces the network costs.

With this regards, three interconnected DWDM rings (Figure 4.2) were proposed to develop the Tanzanian ICT backbone infrastructure during preliminary design stages. This network topology constituted 20 cities plus two districts (towns) in Tanzania. Four cities (nodes) where these rings interconnect were installed with optical cross-connect switches (OXC). Another 16 cities plus two districts were installed with reconfigurable add/drop multiplexers ROADM).

With this network topology it was difficult to achieve a good DWDM system performance using the simulation software, this was due to the long length of every DWDM ring; such a design required more than one regenerator (section 4.4.6.6) to be installed in each DWDM ring. Also it required many new SSMFs, conduits and other optical components such as Erbium-doped fibre amplifiers (EDFA) (section 4.4.6.5) in the DWDM system. For these reasons it would be too expensive to develop the Tanzanian ICT backbone infrastructure based on this design.

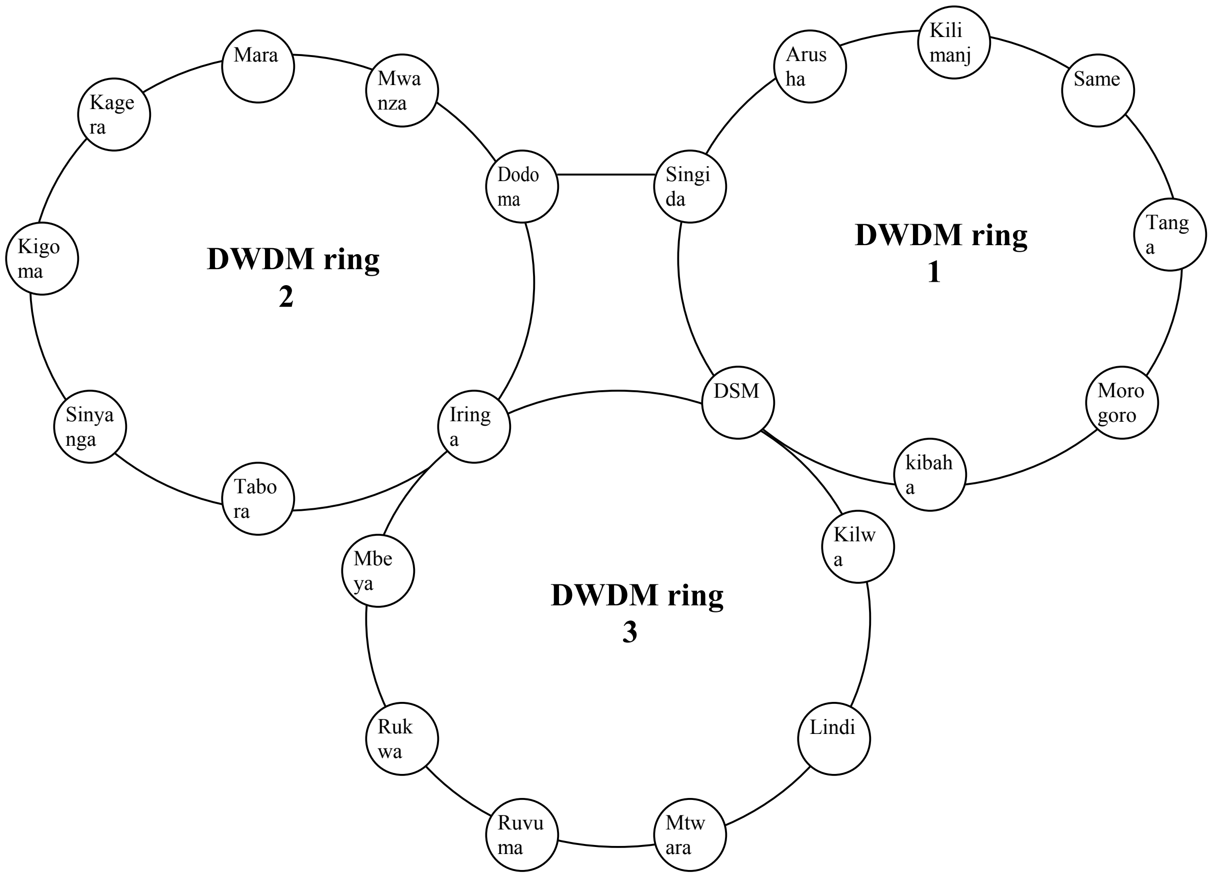

Figure 4.2: Three interconnected DWDM rings

To reduce costs and give good performance the three interconnected DWDM rings were changed into 4-interconnected DWDM network rings (Figure 4.3); which have smaller distances between nodes, and shorter DWDM rings. The distance between 2-nodes in a ring and a total length of one DWDM ring is estimated to be not more than 600 km and 3000 km respectively. The DWDM network nodes represent 21 cities in Tanzania, and each one is installed with a reconfigurable add/drop multiplexer (ROADM) or an optical cross-connect switch (OXC) to meet dynamic traffic demand (section 4.4.2). The ROADM and OXC are outlined with a circle and box respectively in the network topology. The OXC is the DWDM network component that provides cross-connect functionality between input and output ports, each handling a bundle of multiplexed single-wavelength signals [95-99]. The OXC is also an intelligent DWDM network component that can detect failures in the network and rapidly re-route traffic around the failure. The ROADM has similar features to OXC, but it also allows single or multiple wavelengths, dependent upon Internet traffic demand to be dropped and added to a multi-wavelength fibre [95-99].

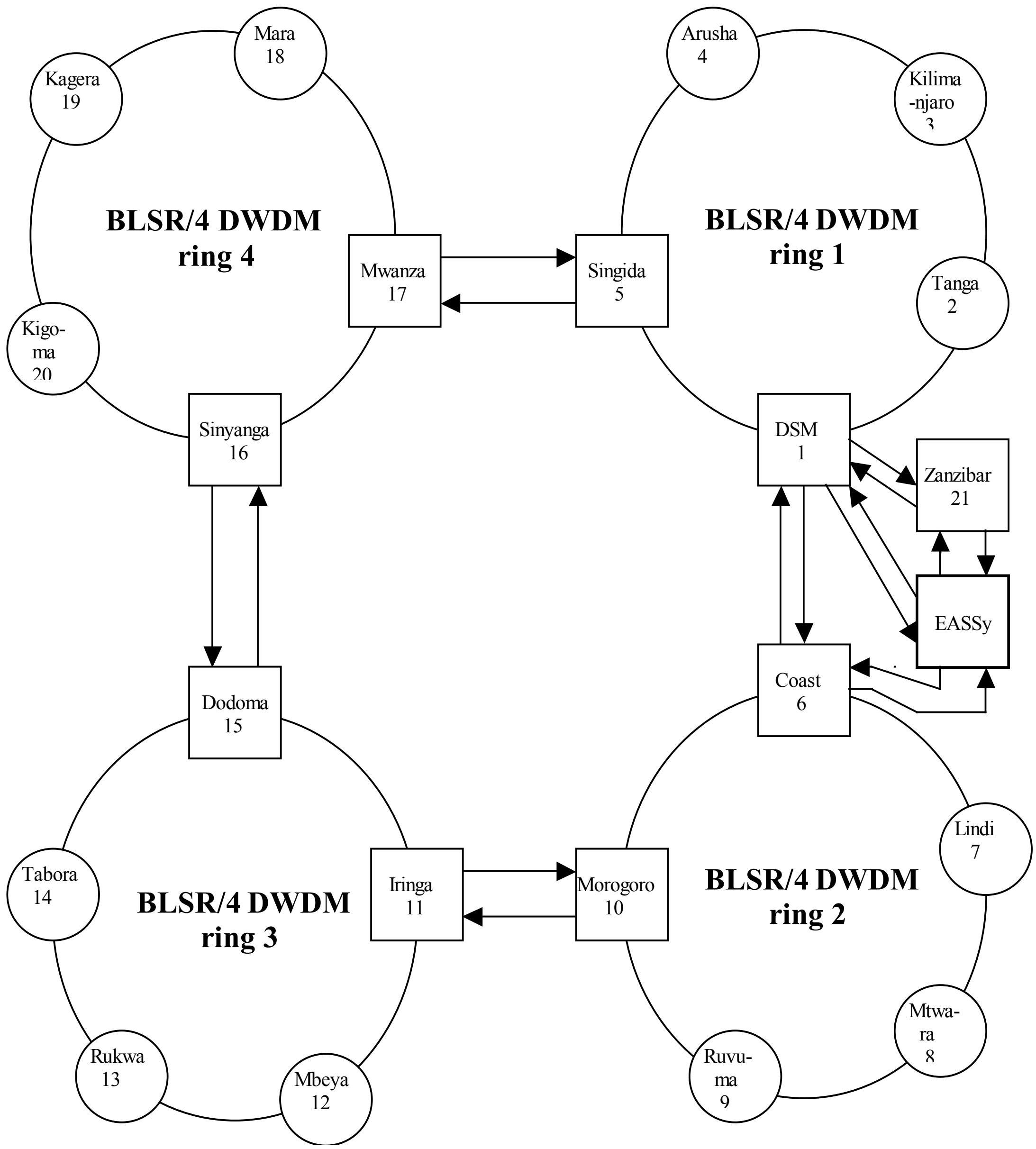

Figure 4.3: Network topology for the deployment of Tanzanian ICT backbone infrastructure

In the DWDM network technology, OXC/ROADM are built with optical switches, multiplexer and demultiplexer [3-5], [45], [93], [100]. Figure 4.4 below illustrates an example of one OXC that interconnects two DWDM rings in the network topology for the deployment of Tanzanian ICT backbone infrastructure. In Figure 4.4, there are four incoming and outgoing SSMFs. Each SSMF carries 40 wavelength channels. A demultiplexer separates each wavelength channel and distributes each wavelength to optical switches, which is placed between the demultiplexer and the multiplexer stages. All signals on a given wavelength are directed to the same optical switch. The optical switch then switches signals and directs them to multiplexers that are associated with the output SSMFs. Finally, signals from multiple DWDM channels are multiplexed before launching them back onto the corresponding output SSMFs. Optical switches inside the OXC/ROADM are built by using 2 x 2 optical space switch, which are arranged in nonblocking architectures as demonstrated in detail in [3-5], [45], [93], [100-102]. These optical switches route a signal from any input to any output on a given wavelength. Since on each DWDM network link there are four SSMFs, and 40 wavelength channels on each SSMF; the OXC is built with four demux/mux and 40 8 X 8 optical switches, as shown in Figure 4.4.

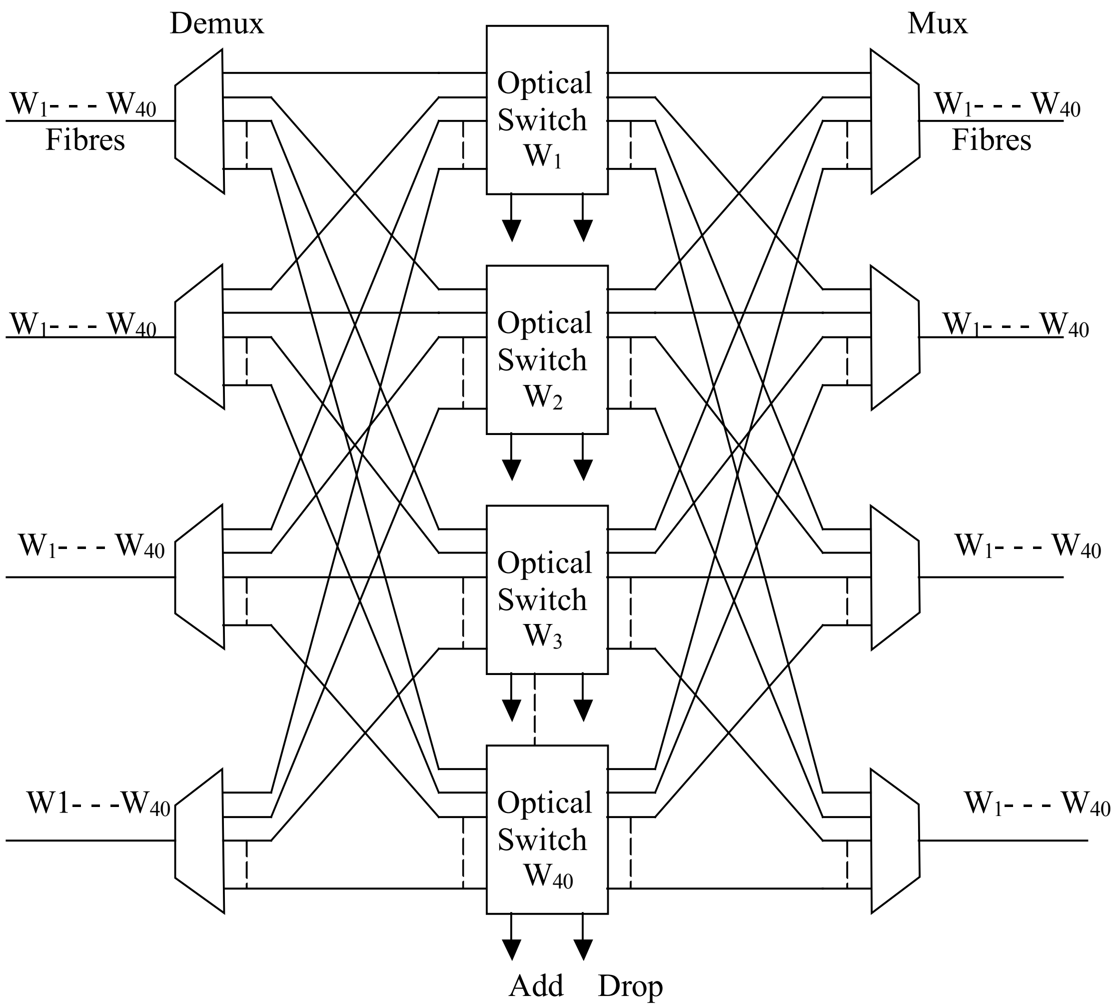

Figure 4.4: Optical crossconnect switch (OXC) architecture

The DWDM ring network is connected to the rest of the world via the East African submarine cable (EASSy) through Dar-es-Salaam (DSM), Zanzibar and Coastal cities [90]. The EASSy system is a DWDM network technology that transmits on 32-wavelengths channels with a data rate of 20 Gb/s on each channel. Tanzania is connected to the rest of the world via the Indian Ocean EASSy cable via South Africa since August 2010, as shown in Figure 4.5. The goal of the EASSy is to support an increase in traffic and Internet services, and connect Africa to the rest of the world; bringing cheap access to more than 250 million people [79]. Thus connecting the ICT backbone infrastructure with EASSy would greatly reduce Internet connection charges in Tanzania.

Figure 4.5: EASSy connection to Tanzania via South Africa

4.4.1. Traffic Protection

Protected optical links between nodes in a DWDM network are realised by the use of four-fibre bi-directional line switched rings (BLSR/4) [90]. For example, Figure 4.6 illustrates how the four-fibre bi-directional line switched rings protect the DWDM ring 1 in the network topology for the Tanzanian ICT backbone infrastructure. A BLSR/4 has two working and protection SSMFs. It employs two types of protection mechanisms: span switching and ring switching [4], [5]. In span switching, if a transmitter or receiver on a working SSMF fails, or a working SSMF is cut on the link between two nodes, the traffic is routed onto the protection SSMF on that link between these two nodes. If both the working and protection SSMFs are cut on the link between two nodes, the traffic is re-routed around the ring by the nodes adjacent to the failure on the protection SSMFs by using ring switching. Also a BLSR/4 can use the protection bandwidth to carry low priority or extra traffic, under normal operation, but this extra traffic is lost in the event of a failure in the DWDM network [4]. However this feature requires additional signaling between the nodes in the event of a failure to indicate to the other nodes that they should operate in protection mode and throw away the low priority traffic.

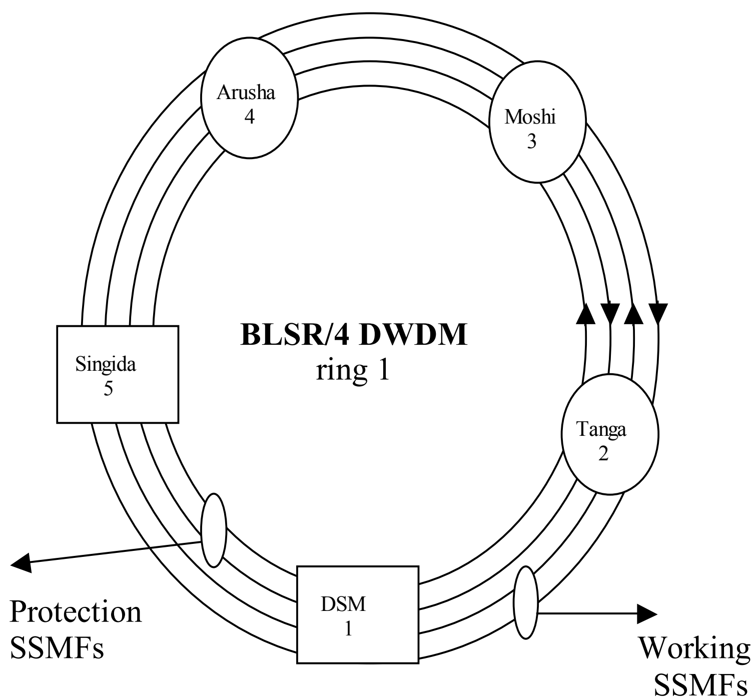

Figure 4.6: BLSR/4 Protection

4.4.2. Dynamic Traffic

Since the Internet traffic has been doubling every year especially in the commercial city, Dar-es-Salaam or in other major cities, for example Mwanza or Arusha, we have chosen the dynamic traffic to meet those demands. The traffic is dynamic if lightpath requests (i.e., Internet traffic) arrive and terminate at random times [103-111]. With dynamic traffic, an existing lightpath can be dropped and a new one established in response to changing traffic patterns or optical network component failures. As we described in section 4.2, Dynamic traffic is configured by the use of OXC or ROADM that add/drop any wavelength in the DWDM network.

4.4.3. Wavelength blocking

This kind of blocking can only occur in DWDM networks [4-5], [92], [93], [103-111]. It happens when there is no capability to assign a lightpath request (i.e., Internet traffic) to an unused wavelength in the DWDM network. Therefore, to avoid this, we prefer 40 wavelength channels (section 4.2), dynamic traffic (section 4.4.2), and dynamic routing and wavelength assignment algorithms (RWA) demonstrated in detail in [103-111]. Note that further discussions regarding dynamic traffic, RWA and wavelength blocking are beyond the scope of this research, for further details see the reference provided.

4.4.4. DWDM network service layers

The DWDM networks are normally decomposed into three layers (Figure 4.7), a physical media layer, an optical layer, and a client layer so as to transmit a data to any other networks [4], [5], [92]. The optical layer is sandwiched between the lower physical media layer and upper client layer. The optical layer performs several functions, such as multiplexing wavelengths, switching and routing wavelengths, and monitoring network performance at various levels in the DWDM network. The optical layer also has been decomposed into three sublayers: an optical channel (OCh-P) layer, an optical multiplex section (OMS) layer, and an optical transmission section (OTS) layer [4].

The functionality of the optical channel layer is to provide end-to-end networking of optical wavelength channels (lightpaths) for transparently conveying the client data signals. The optical multiplex section layer concerns networking of aggregate multi-wavelength optical signals. The optical transmission section layer concerns the transmission of optical signals on SSMF. In short, the optical layer provides client-independent or protocol-transparent circuit switched service to a variety of clients that constitute the client layer (e.g. SONET/SDH, IP routers, ATM, etc). Since the lightpaths can carry data at a variety of bit rates and protocols.

Therefore in our case, the DWDM network for the deployment of ICT backbone infrastructure is designated to take the standard data signal directly from network clients e.g. IP/MPLS routers or via SONET/SDH and convert each data signal to a lightpath. These individual lightpaths are then combined and transmitted onto a SSMF. At the destination node, the reverse process takes place; individual lightpaths are converted directly to IP/MPLS routers or via SONET /SDH muxes. The following sections describe how the optical DWDM network transmits data signals (Internet traffic e.g. IP packets) to/from client layers (e.g. SONET/SDH network and IP/MPLS router) in the Tanzanian ICT backbone infrastructure.

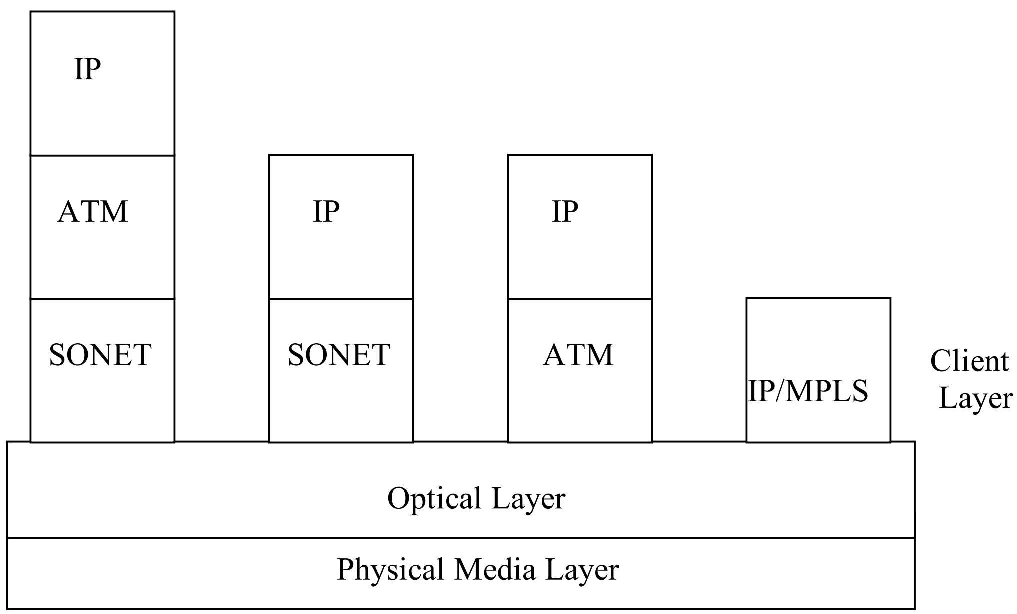

Figure 4.7: DWDM network layers

4.4.4.1. IP over SONET over DWDM

In this scheme, the IP packets (i.e. Internet traffic) are normally encapsulated into point-to-point protocol (PPP) packets framed using higher level data link control (HDLC), or into simple data link (SDL) frames and then transmitted directly over SONET/SDH then to DWDM optical layer [112-115]. For this reason, a SONET/SDH network provides: end-to-end services and an efficient mechanism to multiplex/demultiplex lower-speed connections into or from the DWDM network. For example, low-speed voice connections of 64 Kb/s and Internet traffic of 2 Mb/s can be multiplexed/demultiplexed into or from a 2.5 Gb/s data stream respectively over the DWDM network. Moreover, the protection mechanisms employed in SONET/SDH networks ensure that the service is restored within 50 ms in the event of failures [4], [5]. The key network element of SONET/SDH is add/drop multiplexers (ADM). Hence, the SONET/SDH ADM will operate as the regional network (metro), and be installed at the edge of the DWDM network for grooming traffic at the low bit rates where it is more economic than a DWDM network [116], [117].

4.4.4.2. IP/MPLS over DWDM

In this case, the IP packets are routed directly over the DWDM network by the use of an MPLS router (chapter 2, section 2.2.4.2). Before the development of MPLS router, in an IP network (PDSN) every IP packet was processed by an IP router before forwarding to the next router. The processing included examining and mapping the long IP addresses carried by the IP packet and determining the next hop by looking up the local routing table. This kind of IP packet forwarding was slower due to the long packet processing time; the MPLS router enables fast forwarding of IP packets. The use of an MPLS router for forwarding IP packets enables direct integration of IP/MPLS router and DWDM without needing any intermediate layer (e.g. SONET/SDH or ATM) between the IP layer and the DWDM layer, resulting in significant overhead savings. The following are commonly adopted interaction models used to integrate IP over DWDM via MPLS routers [28-32]:

In the overlay model

In this model, The IP-MPLS layer and optical layer are managed and controlled independently. Two distinct control planes exist, each corresponding to a different layer (Figure 4.8). Here, the optical layer acts as the server and the IP-MPLS layer acts as the client. The lightpath services are provided by the optical layer to the IP-MPLS layer, the IP-MPLS layer treats a lightpath (in the optical layer) as a link between two IP/MPLS routers. The topology perceived by the IP-MPLS layer is the virtual topology; in which the IP/MPLS routers are interconnected by lightpaths. The topology perceived by the optical layer is a physical topology; in which the OXC/ROADM is interconnected by physical fibre links.

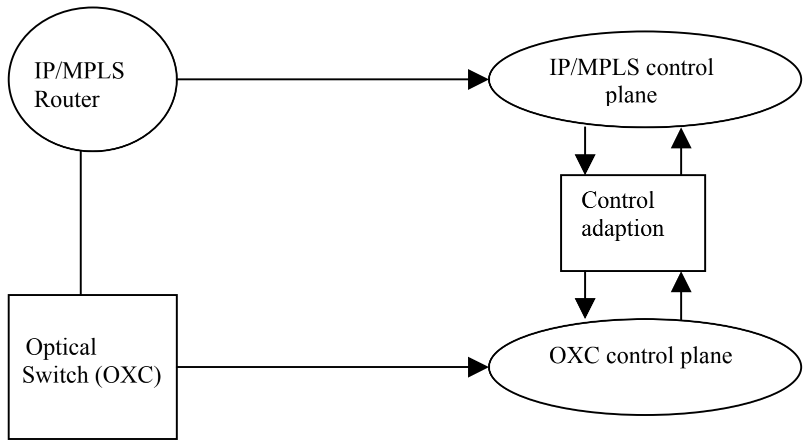

Figure 4.8: Overlay Model

Integrated model

In this model, the IP-MPLS router and an OXC/ROADM are together treated as a single network element. The functionality of both IP/MPLS router and DWDM network are integrated at each network element so that the resource at both the IP-MPLS and optical layers can be utilised in an efficient way. The topology perceived by the layers is a single integrated IP-MPLS /DWDM network topology, with the lightpaths viewed as tunnels. These two layers provide a single unified control plane (Figure 4.9). The integrated model amends naturally to the distributed implementation, where the overlay mode is more suitable for centralised implementation. The integrated model can manage resources more dynamically and respond faster to traffic changes than the overlay model. However, the integrated model is more complex to implement, as the capability of the existing network elements needs to be enhanced to provide a single control plane. Also, the distributed implementation makes the integrated model difficult to synchronize between the integrated network elements to ensure up-to-date and consistent network state information. The overlay model is preferred to integrate IP/MPLS router with DWDM network for the development of the Tanzanian ICT backbone infrastructure.

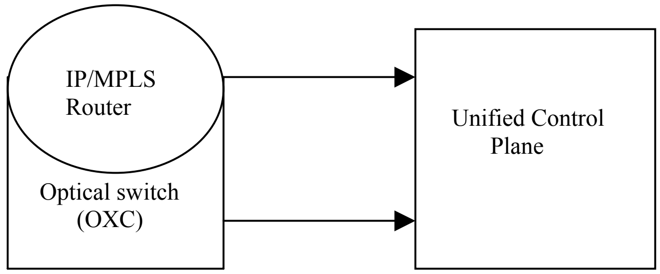

Figure 4.9: Integrated Model

4.4.5. Network Management system (NMS)

In the DWDM network for the deployment of Tanzanian ICT infrastructure, a network management system [4], [92] is needed to setup and tear down lightpaths. A lightpath is an all-optical communication path between two nodes, established by allocating the same wavelength channel throughout the route of the transmitted data. A lightpath can carry data at up to several gigabits per second, and is uniquely identified by a physical path and a wavelength channel. Therefore, when a connection (lightpath) request arrives, The NMS must be able to select a route, assign a wavelength to the connection, configure the appropriate switching node along the route, and provide information such as what are the existing lightpaths and which wavelengths are currently being used on each SSMF link so as to avoid wavelength blocking (section 4.4.3).

The most important functions of the network management system are to minimise the lightpath setup times, and minimise the bandwidth used for control signals. Other functions performed by a network management system include performance management (monitoring and managing the various parameters, such as throughput, wavelength utilisation, and bit error rate, which measure the performance of the network), fault management (detecting and isolating failed components, and restoring the disrupted traffic), security management (protecting data belonging to network users from being tapped or corrupted by unauthorised users), and accounting management (tracking the usage of network components and charging/billing) [4].

The NMS can be either centralised or distributed. A distributed NMS is generally preferred, as it is much faster than centralised systems, even in a DWDM network with only a few nodes. Another reason for using distributed NMS arises when the DWDM network becomes very large (i.e. with many nodes). In this case, it becomes difficult for a single centralised system to manage the entire network. Furthermore, DWDM networks could include multiple domains administered by different managers. The managers of each domain will need to communicate with managers of others domains to perform certain functions in a coordinated manner. A distributed NMS is implemented in a hierarchical manner with the use of sub NMS, which are called element management systems (EMS) [4]. DWDM optical components (network elements) such as optical line terminals (OLTs), reconfigurable optical add/drop multiplexers (ROADMs), optical amplifiers (EDFAs), and crossconnect switches (OXCs) usually incorporate built-in agent (software), which in turn communicates with their corresponding EMS through a network. An optical supervisory channel (OSC), e.g. a dedicated wavelength channel is required for control and management performance between network elements. Finally, the EMS communicates with a NMS [4]. With reference to the ring DWDM topology (Figure 2.10), the network can operate in a centralised mode using a single NMS. The NMS acts as a server, which communicates with all OXC/ROADMs (nodes) in the network. In doing so, the NMS can perform the following functions in the DWDM network: control management of signals; wavelength management; fault management and security management. To operate in a distributed mode, each node will play a role as a server, and communicates directly to each other to perform the same function.

4.4.6. Optical DWDM network components

This section describes in detail the following optical components, which are also installed in the DWDM network, apart from OXCs and ROADMs (section 4.4), for the deployment of a Tanzanian ICT backbone infrastructure.

4.4.6.1. Standard single mode fibres (SSMFs)

Optical fibre consists of a very fine cylinder of glass (core) in which light propagates. The core is surrounded by a concentric layer of glass (cladding), which is protected by a thin plastic jacket as shown in Figure 4.10. The core has a slightly higher index of refraction than the cladding. The ratio of the indices of refraction of the cladding and the core defines the critical angle. What makes fibre optics work is total internal reflection: when a ray of light from the core approaches the core-cladding surface at an angle more than θ_c, the ray is completely reflected back into the core. Since any ray of light incident on the core cladding surface at an angle more than θ_c (critical angle) is reflected internally, many different rays of light from the core will be bouncing at different angles. In such a situation, each ray is said to have a different transverse mode and hence a fibre having this property is called a multimode fibre (Figure 4.11), which have a core diameter approximately 50µm to 85µm. Multiple transverse modes cause the rays to interfere with each other, thereby limiting the maximum bit rates that are achievable using a multimode fibre [4]. However, SSMF have a very narrow core diameter (i.e. 8 µm to 10 µm), which makes the light travel in a straight line along the centre axis of the fibre; hence allowing propagation of a single transverse mode (Figure 4.12). This property permits the SSMF to transmit data at several gigabits per second over hundred of kilometers in a DWDM network. Detailed discussions of light rays propagating in multimode and single mode fibres can be found in [3] and [4].

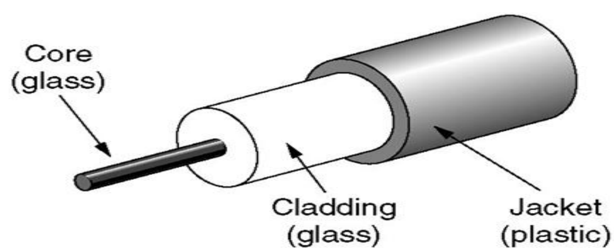

Figure 4.10: An optical fibre

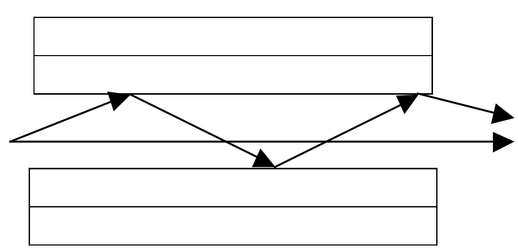

Figure 4.11: Multimode fibre (multiple transverse modes)

Figure 4.12: Single mode fibre (only one mode propagates in a fibre)

4.4.6.2. Transmitters

The role of an optical transmitter is to convert the electrical signal into optical form and to launch the resulting optical signal into a SSMF. Figure 4.13 shows the block diagram of an optical transmitter. It consists of an optical source, an external modulator, and a channel coupler. We have used a laser source with a narrow spectral width, the distributed-feedback (DFB) laser [4] along with an external modulator to transmit a data rate of 2.5 Gb/s per wavelength channel. Tunable lasers are used to enable dynamic configuration in the DWDM networks. As demonstrated in [3-5], [118] there are different approaches for realizing tunable lasers but this is beyond the scope of this research.

The process of encoding data onto the laser source is called modulation. The simplest and most widely used modulation scheme is called on-off keying (OOK), where the laser source is turned on or off, depending on whether the data bit is a 1 or 0. OOK modulated signals are usually realised in one or of two ways: (1) by direct modulation of a semiconductor laser or (2) by using an external modulator. In direct modulation, the drive current into the semiconductor is set well above threshold for a 1 bit and below (or slightly above) threshold for a 0 bit. The ratio of the output powers for the 1 and 0 bits is called the extinction ratio. Direct modulation is simple and inexpensive since no other components are required for modulation other than the laser source itself. The disadvantage of direct modulation is that the resulting pulses are considerably chirped. Chirp is a phenomenon wherein the carrier frequency of the transmitted pulse varies with time, and it causes a broadening of the transmitted spectrum [3-5]. Therefore in this research, we have used an external modulator in front of the laser source (see appendix 2), which results in less chirp and permits data transmission over long distances [90], [91], [119], [120]. The most common OOK modulation signal formats are non-return-to-zero (NRZ) and return-to-zero (RZ). In the NRZ format, the pulse for a 1 bit occupies the entire bit interval, and no pulse is used for a 0 bit. If there are two successive 1's, the pulse occupies two successive bit intervals. In the RZ format, the pulse for a bit occupies only a fraction of the bit interval, and no pulse is used for a 0 bit. The NRZ was preferred over RZ because the signal in NRZ format occupies a much smaller bandwidth about half that of the RZ format, and is suitable for the transmission of 2.5 Gb/s over longer distances. The coupler in a transmitter block diagram is typically a micro-lens that focuses the optical signal onto the entrance of a SSMF with the maximum possible efficiency.

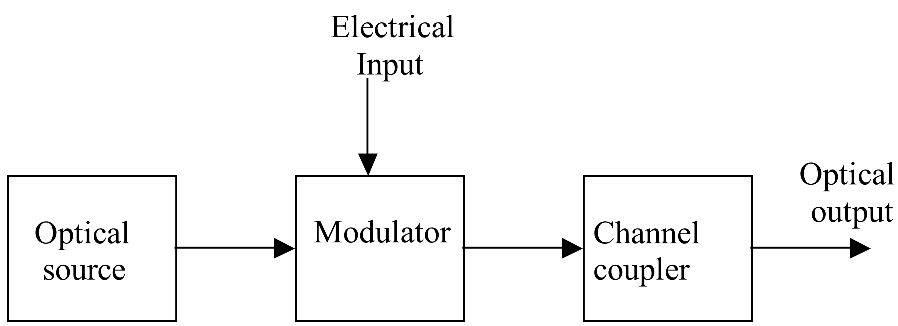

Figure 4.13: Block diagram showing the components of an optical transmitter

4.4.6.3. Receivers

An optical receiver converts the optical signal received at the output end of SSMF back into the original electrical signal. Figure 4.14 shows the block diagram of an optical receiver. The coupler focuses the received optical signal onto the photo-detector. The optical signal is converted to an electrical current, and then the electrical signal is amplified by the use of a front-end amplifier. The filter then filters the amplified electrical current to minimise the noise outside the bandwidth occupied by the signal. The filter also shapes the pulses so that the bit error rate is minimised, and a decision circuit determines whether the transmitted bit was 1 or 0 in each bit interval. The accuracy of the decision circuit depends on the signal-to-noise ratio (SNR) of the electrical signal generated by the photo-detector.

The performance of an optical DWDM network is characterised through the bit-error rate (BER). The required BER for an optical network is in the range of 10^{-9} to 10^{-15}, a typical value is 10^{-12}. The BER of 10^{-12} corresponds to one allowed bit error for every terabit of data transmitted on average. An important parameter that is indicative of receiver performance is called receiver sensitivity. It is usually defined as the average optical power required to achieve a certain bit error rate at a particular data rate, it is usually measured at a bit error rate of 10^{-12} for a good optical network performance. Receiver sensitivity depends on the SNR, which in turn depends on various noise sources that corrupt the signal received. Even for a perfect receiver, the process of photo-detection itself introduces some noise. This is referred to as the quantum noise or the shot noise, as it has its origin in the particle nature of electrons. Optical receivers operating at the shot-noise limit are called quantum-noise limit, since many other noise sources decrease the SNR considerably below the shot-noise limit. Some of the noise sources such as thermal noise and amplifier noise are internal to the receiver. Others originate at the transmitter or during propagation inside the SSMF. For instance, the optical signal launched by the transmitter has intensity and phase fluctuations that have their origin in the fundamental process of spontaneous emission.

Also the chromatic dispersion in SSMF can add additional noise through phenomena such as intersymbol interference and mode-partition noise. As a result some techniques have been used in this research to minimise all these errors (system impairments) in the optical DWDM network in order to achieve the required BER at the receiver for good DWDM system performance as discussed in chapter 5, also see [90], [91], [119], [120]. The most common types of receivers are APD and pin receivers. In this research, we have used APD receivers (see appendix 3), which have higher sensitivities than pin receivers, which achieve the required BER for good DWDM system performance for the transmission rate of 2.5 Gb/s.

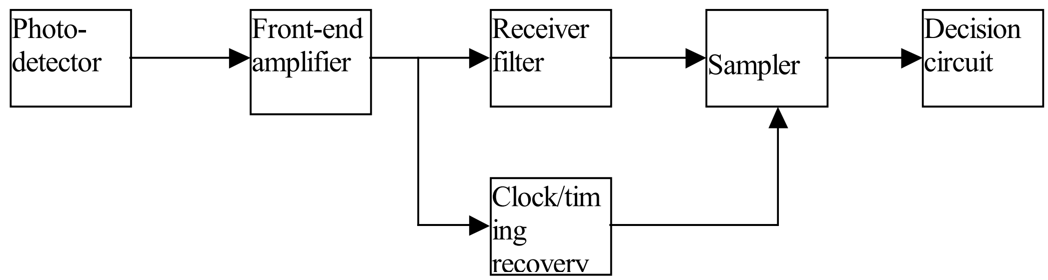

Figure 4.14: Block diagram showing the components of an optical receiver [4]

4.4.6.4. Multiplexers & demultiplexers

Multiplexers combine signals at different wavelengths on its input ports onto its output port for signal transmission in a SSMF, and demultiplexers perform the opposite function. Multiplexers and demultiplexers are used in optical DWDM network terminals as well as in larger wavelength crossconnect switches (OXC) and configurable or reconfigurable add/drop multiplexers (OADM or ROADM). Multiplexers/Demultiplexers (MUX/DEMUX), which have been used in the proposed DWDM network are made either by the use of thin-film resonant multicavity filters (TFMFs) or arrayed waveguide gratings (AWGs) [3-5].

A thin-film resonant multicavity filter (TFMF) consists of two or more cavities separated by reflective dielectric thin-film layers. In order to obtain a multiplexer or demultiplexer, a number of these filters are cascaded, as shown in Figure 4.15. Each filter passes a different wavelength and reflects all the others. When used as a demultiplexer, the first filter in the cascade passes one wavelength and reflects all the others onto the second filter. The second filter passes another wavelength and reflects the remaining ones, and so on. This device is extremely stable with regard to temperature variations; it also has low loss and is insensitive to the polarization of the signal. An arrayed waveguide grating (AWG), which consists of two multiport couplers interconnected by an array of waveguides can also be used either as a multiplexer or demultiplexer. To perform as an N X 1 wavelength multiplexer; N input signals at different wavelength channels are combined onto the single output coupler. It can perform as a demultiplexer by doing the inverse process, which is the 1 X N wavelength demultiplexer. Another way to understand the operation of the AWG as a demultiplexer is to think of the multiport couplers as lenses and the array of waveguides as a prism. The input coupler collimates the light from an input waveguide to the array of waveguides. The array of waveguides act like a prism, providing a wavelength dependent phase shift, and the output coupler focuses different wavelengths on different output waveguides. An AWG has lower loss, flatter passband, and is easier to realize on an integrated optical substrate.

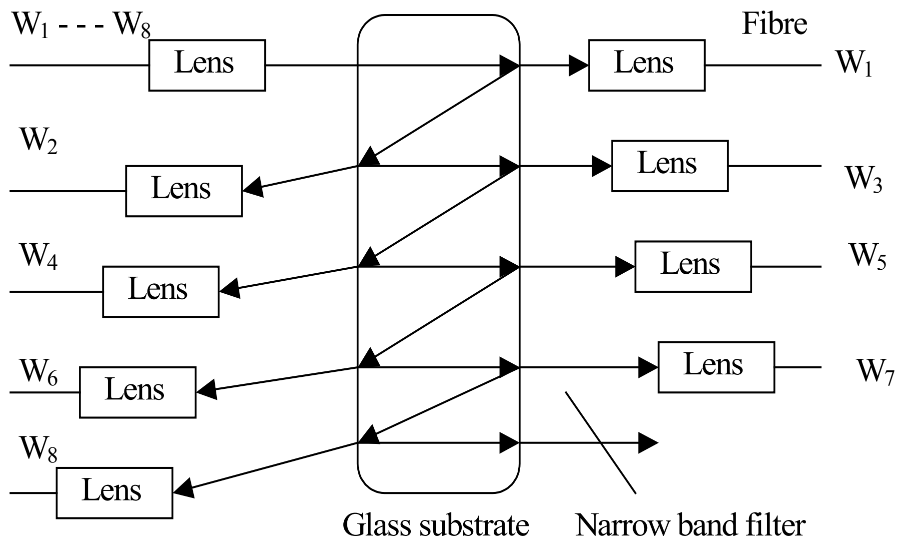

Figure 4.15: Mux/demux by using TFMF [4]

4.4.6.5. Erbium-doped fibre amplifier (EDFA)

In an optical DWDM network, the SSMF normally attenuates the optical signals from the transmitter as they propagate through it. Other optical components in the optical system such as optical switches, MUX/DEMUX also add loss to the DWDM network. After some distance, the cumulative loss of signal strength causes the signal to become too weak to be detected. As shown in the block diagram, Figure 4.16, an erbium-doped fibre amplifier (EDFA) provides amplification of the optical signals in the DWDM system by pumping the erbium atoms in the SSMF from their ground state to an excited state at a higher energy level using a pump laser source operating at a wavelength of 980nm or 1480nm [3-5]. An incoming signal photon triggers these atoms to come down to their ground state, in the process, each atom emits a photon. Thus incoming signal photons trigger the emission of additional photons, which increase the strength of the optical signal. We have used the flat gain EDFAs that operate in the C-band, which has a gain bandwidth of about 35 nm in the 1.55 µm wavelength region of SSMF operation. This spectral range supports 40 DWDM signal channels with a separation of 0.8 nm between channels (corresponding to 100 GHz, ITU standard). Three different types of EDFAs have been used in this research for the deployment of a DWDM system [90], [91], [119], [120]: A power amplifier (see appendix 4), which is installed after a transmitter to increase the output power; a line amplifier, which is used typically in the middle of the link to compensate for link losses; An optical preamplifier, which is used just in front of a receiver to improve its sensitivity.

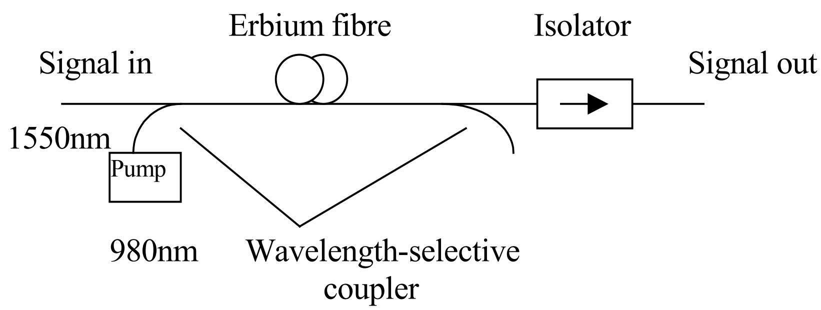

Figure 4.16: An erbium-doped fibre amplifier (EDFA) [4]

4.4.6.6. Regenerators

When the signal is transmitted more than the maximum length in a DWDM system ring (e.g. over 3000 km), it become too weak to detect reliably, this is due to the SSMF losses, which are caused by various system impairments [91], [119]. Hence, a regenerator must be used to regenerate the optical signal. A regenerator is a receiver-transmitter pair that detects the incoming signal and restores the signal to noise ratio by modulating the optical source. However, when EDFA (section 4.4.6.5 above) is used for a longer distance, it adds noise and worsens the impact of SSMF dispersion. As a result signal degradation keeps on accumulating over multiple amplification stages and this weakens the signal. In contrast, regenerators do not suffer from this problem, since they regenerate the original bit stream periodically and thus effectively compensate for both SSMF loss and dispersion in the DWDM network. However, regenerators are very expensive to use compared to EDFA

4.5. Access Networks

Access networks are used to provide ICT services such as voice or Internet traffic to the majority of Tanzanian people who live in both urban and rural areas. In some urban areas, digital subscriber line (DSL) network (chapter 2 section 2.1.2) such as ADSL is available, which uses existing copper telephone lines to deliver broadband data rates to customer premises. More than 90 percent of the country's existing urban copper telephone lines belong to TTCL [64] and were deployed for telephony purposes, but nowadays provides Internet services as well. Hence DSL will be used in urban areas to provide affordable and sufficient data rates for Internet services applications. In other urban and most rural areas where there are no existing copper telephone lines, the worldwide interoperability for microwave access (WiMAX) (chapter 2 section 2.4) will be used to provide Internet services. Therefore the DSL and WiMAX will be connected to metro networks such as SONET/SDH or IP/MPLS router onto the ICT backbone infrastructure to provide voice and Internet service to the majority of Tanzanian people who live in both urban and rural areas.

4.6. Conclusion

In this chapter, we have presented the ICT backbone infrastructure concept that exploits an optical DWDM network technology, and also shown how it can be implemented easily by the use of existing standard single mode fibre (SSMFs) and other optical components. We also explain how using a relatively low bit rate, e.g. 2.5 Gb/s per wavelength channel makes the DWDM network less vulnerable to system impairments such as chromatic dispersion, polarization-mode dispersion, and nonlinearity effects, which reduces DWDM network costs. Also, we have revealed that multiple wavelength channels in a DWDM network is an attractive solution for deploying ICT backbone infrastructure from an economic point of view, because it provides a sophisticated control plane to assign and switch wavelengths across users independently of each other. We have also demonstrated how the optical links between nodes in a DWDM network are protected by the use of four-fibre bi-directional line switched rings (BLSR/4) in case of fibre cut or optical components failure. Moreover, we have shown our ICT backbone infrastructure can yield enough capacity to cope with the increasing traffic demand in Tanzania. Also it can be an effective solution for reduction of the Internet connection charge, since it will be connected by means of the East African submarine cable (EASSy) to the rest of the world. This is a more cost effective solution than the existing ICT infrastructures, which connects ICT users by means of Satellite links to the rest of the world. Furthermore, we have briefly explained how the metro networks (e.g. SONET/SDH and IP/MPLS) incorporating an access network (e.g. DSL and WiMAX) would be connected onto the ICT backbone infrastructure to provide ICT services to the majority of the people who live in both urban and rural areas.

CHAPTER 5. ANALYSIS AND PERFORMANCE OF DWDM SYSTEM

5.1. Introduction

Chapter 4 describes an optical DWDM network for the deployment as an ICT backbone infrastructure, which comprises the following optical components: OXCs, ROADM, SSMFs, Transmitters, Receivers, EDFAs, Multiplexers (MUX), Demultiplexers (DEMUX) and regenerators. These components allow a DWDM system to transmit data to any other network clients e.g. IP/MPLS router, SONET/SDH or ATM network. Data are converted into electrical signals and coded to the non-return-to-zero (NRZ) modulation format, then converted into light signals, and assigned a wavelength channel for transmission by means of a transmitter. The signals from the different wavelength channels are combined into a SSMF by a DWDM multiplexer and after a transmission distance of 120 km, amplified using EDFAs (incorporating DCFs). The EDFAs, which are deployed in the DWDM system operate in the C-band over the range of 1530 nm to 1565 nm, about a 35 nm line width. This spectral range supports 40 DWDM signal channels with a separation of 0.8 nm between channels (corresponding to 100 GHz, ITU standard). The DWDM demultiplexer separate out the DWDM signal channels with minimum system impairments and directs them to the individual channel receiver, which converts an optical signal into an electrical signal. The receiver comprises of a photodetector to generate an electrical current, it has a front-end amplifier to increase the power of the generated electrical signal, a filter to minimise noise in the amplified electrical current, and a decision circuit to determine whether the transmitted bit was 1 or 0 in each bit interval (Figure 4.11).

This chapter analyses various system impairments (section 5.2), which can occur in the DWDM system when transmitting the signal on the SSMFs. Also it discusses the measurements (section 5.3), which are used to determine the signal loss due to the system impairments in DWDM systems, and finally it analyses and compares the performance of the DWDM system (section 5.4) when the data rates of 2.5 Gb/s and 10Gb/s are transmitted in Figure 4.3

5.2. System Impairments Analysis

5.2.1. Attenuation loss

Attenuation is the one of system impairments that occurs in a DWDM system, which leads to a loss of signal power as the signal propagates over a prescribed length of SSMF [3-5]. The attenuation loss is related in [4] by the equation (5.1):

$$P_{out} = P_{in}\, e^{-\alpha L} \qquad (5.1)$$

Where α = represents the SSMF attenuation, L = SSMF length, P_{out} = signal output power at the end of SSMF, and P_{in} = Signal Input power.
Normally, attenuation (α) is expressed in units of dB/km, thus for an SSMF length of 1km; the attenuation of the SSMF from above equation can be expressed as in equation (5.2):

$$-\alpha = 10 \log_{10} P_{out} / P_{in} \qquad (5.2)$$

The attenuation loss is primarily due to material absorption (water vapor) in SSMF and Rayleigh scattering (when the medium is not absolutely uniform, it causes small fluctuations in the refractive index, which in turn causes the light to be scattered and thereby attenuates the propagating signal). The material absorption loss is negligible in the wavelength region of 1550 nm in which the SSMF operates. Thus, the attenuation loss is mainly caused by Rayleigh scattering, and is approximately 0.2dB/km on the SSMF. For example to transmit a signal on the SSMF for a distance of 120 km in the DWDM system will undergo a link loss of about 24 dB before it is amplified. For this reason, the erbium-doped fibre optical amplifier (EDFA) described in detail in chapter 4 (section 4.4.5.6), has to be installed at each end of SSMF link in the DWDM system to compensate for attenuation loss, however this compensation will result to optical noise in the DWDM system as described below.

5.2.2. Signal-spontaneous noise

Optical amplification is not possible without the generation of amplified spontaneous emission (ASE), and the noise resulting from this ASE constitutes perhaps the most severe system impairments that limit the reach and capacity of the DWDM system [5]. Each EDFA contributes ASE, which can be expressed as:

$$P_{ASE}\ (\text{mW}) = 2hv.\Delta v.n_{sp}\ (G\text{-}1) \tag{5.3}$$

Where P_{ASE} is the ASE power (noise) in an optical bandwidth Δv, h is Planck's constant, v is the optical frequency, n_{sp} is the spontaneous emission factor, and G is the EDFA gain.

These contributions add cumulatively along the EDFA chain, and gives rise to signal spontaneous beat noise at the receiver, which is the fundamental noise limit in an EDFA transmission system.

The signal-spontaneous noise impairment can be characterised in terms of the optical signal to noise ratio (OSNR) as shown in equation (5.4), and is defined as the ratio of the signal channel power to the power of the ASE in a specified optical bandwidth.

$$\text{OSNR (dB)} = \frac{P_{out}}{2hv.\Delta v.n_{sp}\ (G - 1)} \tag{5.4}$$

5.2.3. Chromatic Dispersion

This type of dispersion occurs in a DWDM system, and is the widening of pulse duration as it travels through a SSMF. As a pulse widens, it can broaden enough to interfere with neighboring pulses on the SSMF, leading to a bit error at the receiver [3-5]. The approximate dispersion limit for a non-return-to-zero (NRZ) data signal by using an external modulator along with a distributed feedback (DFB) laser is given in [5] by equation (5.5):

$$D\ (\text{ps/nm}) = \frac{104000}{B^2} \tag{5.5}$$

Where D is chromatic dispersion in ps/nm and B is a bit rate in Gb/s. SSMF has a total dispersion of 17 ps/nm-km in the lower loss wavelength region of 1550 nm. Therefore the data transmission of 2.5 Gb/s and 10 Gb/s will be limited up to approximately distances of 980 km and 60 km respectively as per equation 5.5.

In order to compensate for chromatic dispersion in a DWDM system that uses SSMF, chromatic dispersion compensating fibres (DCFs) are used. DCFs are normally employed when external modulation is not sufficient, especial for data transmission of 10 Gb/s or more data rate per wavelength channel. DCF provides negative chromatic dispersion in the 1550 nm wavelength region. Example: a 120 km distance of SSMF has an accumulated or total chromatic dispersion of 17 ps/nm x 120 km = 2040 ps/nm-km.

Thus a DCF with a chromatic dispersion of –2040 ps/nm-km can be used to compensate for this accumulated chromatic dispersion to yield a net zero chromatic dispersion. The DCF are normally installed in each EDFA site, so as to compensate for chromatic dispersion.

Since the chromatic dispersion varies for each channel, it is not possible to compensate for the entire system using a common DCF. Another stage of compensation, chromatic dispersion slope compensation must be used to compensate this variation of the total chromatic dispersion. Unfortunately, using the above dispersion compensation techniques in a DWDM system will result in signal losses, Example: The DCF of –2040 ps/nm-km has total loss of 10 dB or more. As a result, nonzero-dispersion fibre (NZ-DSF)(or G.655 according to the ITU standard) have been developed to reduce the pulse spreading due to chromatic dispersion, and also to reduce penalties due to nonlinearities. NZ-DSFs are designed to have a small nonzero value of the dispersion in the 1550 nm wavelength region, and are used on many recently implemented DWDM systems to replace the existing SSMF; this eliminates the need for DCFs.

5.2.4. Polarization mode dispersion (PMD)

PMD is caused by the difference of propagation velocities of light in the orthogonal polarization states of the transmission medium. Like fibre dispersion, PMD causes the transmitted optical pulse to spread out due to the polarization modes traveling at different speeds; this can scramble the signal [4], [97]. This often occurs at high data rates of 10 Gb/s or more per wavelength channel.

The time-average differential time delay between two orthogonal polarization states of the transmission medium is expressed as:

$$\Delta_{\Gamma} = D_{PMD}\sqrt{L} \tag{5.6}$$

Where Δ_{Γ} is called the differential group delay (DGD), L is the fibre link length, and D_{PMD} is the fibre PMD parameter, measured in ps/$\sqrt{km}$. The PMD parameter for a typical fibre lies between 0.5 and 2 ps/$\sqrt{km}$.

However, carefully constructed new fibres have PMD as low as 0.05 to 0.1 ps/$\sqrt{km}$. For the PMD of 0.1 and 0.05 ps/$\sqrt{km}$, a data rate of 10 Gb/s can be transmitted up to the maximum distance of 400 km and 10,000 km respectively, as is proven in [97] by equation (5.7)

$$\Delta_{\Gamma} = B\sqrt{\sum_{K=1}^{M} D_{PMD}(k)^2 L(k)} \tag{5.7}$$

Where B is the bit rate, k is a fibre span that has length L(k), M = is the maximum number of fibre spans in the link. Equalization can be used to compensate for PMD, normally for a data rate of 10 Gb/s, the equalization is carried out in the electronic domain.

5.2.5. Non-Linear effects

The above analyses of system impairments were made by assuming linearity in the DWDM system, which operates at moderate power (a few milliwatts) and at data rates up to 2.5 Gb/s per wavelength channel. However, at higher data rates such as 10 Gb/s per wavelength channel and above or higher transmitted powers, it is important to consider the effect of non-linearity in the DWDM system [121-124].

Nonlinear effects in a DWDM system leads to attenuation, distortion, and cross-channel interference, these effects place constraints on the spacing between adjacent wavelength channels, limit the maximum power on any channel, and corrupts the bit rate at the receiver. The nonlinear effects are: Stimulated Raman scattering (SRS), Stimulated Brillouin scattering (SBS), Self-phase modulation (SPM), Cross-phase modulation (XPM), and Four-wave mixing (FWM).

SRS is caused by the interaction of the optical signal with silica molecules in the SSMF. This interaction can lead to the transfer of power from lower wavelength channels to higher wavelength channels;

SBS is caused by the interaction between the optical signal and acoustic waves in the optical fibre. This interaction can cause the power from the optical signal to be scattered back towards the transmitter.

Self-and cross-phase modulation and four-wave mixing are caused because, in an SSMF, the index of refraction depends on the optical intensity of signals propagating through the SSMF. **SPM** is caused by the variations in the power of an optical signal and results in variations in the phase of the signal. **XPM** is due to a change in intensity of a signal propagating at a different wavelength. **FWM** occurs when two or more optical signals (wavelengths) mix in such a way that they produce new optical frequencies called sidebands, which can cause interference if they overlap with the frequencies of a signal.

5.2.6. Crosstalk

Crosstalk is unwanted signal that affects the desired signal in a DWDM system. The optical components such as filters, switches, Mux/Demux and an optical fibre introduce crosstalk signal in the system. Two forms of crosstalk arise in the DWDM system: Interchannel and intrachannel crosstalks [4].

Interchannel arises when the crosstalk signal is at a wavelength channel sufficiently different from the desired signal wavelength channel that the difference is larger than the receiver electrical bandwidth. Interchannel crosstalk also occurs through more indirect interactions, for example, if one wavelength affects the gain seen by another wavelength, as with nonlinearities (section 5.2.5 above).

For example in an optical switch, the Interchannel crosstalk can arise due to the imperfect isolation between the switch ports. Also it can occur when the optical filter or Demux selects one wavelength and imperfectly rejects the others.

Intrachannel occurs when the crosstalk signal is at the same wavelength as that of the desired signal or sufficiently close to it that the difference in wavelengths is within the receiver electrical bandwidth. For example, in a joint Demux/Mux device, the demux usually separates the incoming wavelength channel to different output SSMFs. However, in some cases a portion of the signal from one wavelength leaks into the signal of the adjacent wavelength because of non-ideal suppression within the Demux. In this case, when the wavelength are combined again into a SSMF by the Mux, a small portion of that signal leaked into another wavelength will also leak back into the SSMF at the output. Since it is not in phase with the original signal of the adjacent wavelength due to different delays encountered between them, this will result in the intrachannel crosstalk.

The signal power loss (power penalty) due to intrachannel and interchannel crosstalks are given in [4] by equations (5.8) and (5.9) respectively as follows:

$$\text{Power penalty (PP)} = -5 \log (1-2\sqrt{\varepsilon}) \tag{5.8}$$

$$\text{Power penalty (PP)} = -5 \log (1-\varepsilon) \tag{5.9}$$

ε is the crosstalk signal power, in case of N interfering wavelength channels in the

DWDM system ε is expressed in [4] as: $\sum_{i}^{N} \varepsilon_i$ (5.10)

Crosstalk can be removed during the design stages of optical components [4], for example in optical switches it can be removed by adding unused ports. As well as in Mux/Demux, it can be removed by adding an additional filter for each wavelength between the Demux and

Mux stages. However in both cases, the optical components number will double, and hence increase the cost of the optical DWDM network.

5.3. Measurements of DWDM System performance

Since the optical DWDM network for the deployment of Tanzanian ICT backbone infrastructure uses the existing SSMFs. These SSMFs provide an excellent data transmission medium with almost limitless bandwidth and distance capability; but they can be the most limiting optical component of the DWDM network due to system impairments such as attenuation, signal-spontaneous noise, chromatic dispersion, polarization mode dispersion (PMD), non-linear effects and crosstalk as discussed in section 5.2 above, which occurs on data transmission in the wavelength region of 1550 nm in the SSMFs. The effect of system impairments leads to signal power loss (power penalty) in the DWDM system as mentioned above. Therefore, the Tanzanian ICT backbone infrastructure must take into account the signal power loss due to system impairments in order to deliver a good DWDM system performance (i.e. achieve the required quality of service (QoS)). For this reason a minimum average power (receiver sensitivity) must be required at the receiver so as to maintain the desired bit error rate (BER). Usually the presence of system impairment effects is identified when the optical signal to noise ratio (OSNR) at the receiver is small or the receiver sensitivity doesn't achieve the specified BER in the DWDM system [91], [119], [120]. The following sections below define BER, receiver sensitivity and optical signal to noise ratio.

5.3.1. Bit error rate (BER)

This is the ratio of corrupted bits to total bits of the signal transmitted that occurs between the transmitter and the receiver. The required BER for data transmission in the DWDM system is in the range of 10^{-9} to 10^{-15}, a typical value is 10^{-12}, the BER of 10^{-12} corresponds to one allowed bit error for every terabit of data transmitted on average (section 4.4.6.3). A BER is difficult to measure, and more difficult to simulate directly. For example, A BER of 10^{-15} results in less than one error per day (i.e. often called error operation), so would take 100-days of operations to achieve a statistically significant measurement [125]. Thus even in the VPI TransmissionMaker DWDM [126], it would take much longer than this to be simulated. Therefore as shown in section 5.4, BER is simulated with the use of the receiver sensitivity.

5.3.2. Receiver sensitivity

The receiver sensitivity is the average optical power required to achieve a certain bit error rate at a particular data rate, it is usually measured at a bit error rate of 10^{-12} for a good DWDM system performance (section 4.4.6.3). Mathematically, BER can be calculated as per equation (5.11), as shown in [5], where Q is the probability that determines 1-bit at the receiver.

$$\text{BER} = \frac{1}{Q\sqrt{2\pi}}\exp\left(-\frac{Q^2}{2}\right) \qquad (5.11)$$

5.3.3. Optical signal to noise ratio (OSNR)

This is the ratio of the average received signal power to the average optical noise power. For a DWDM system that consists of a chain of erbium-doped fibre amplifiers (EDFAs) along the span, each EDFA compensates for the loss of each span; the OSNR is expressed in [5] as:

$$\text{OSNR (dB)} = 58+P_{out} - L_{span} - \text{NF} - 10\text{Log}\,(N_{amp}) \qquad (5.12)$$

Where P_{out} (in dBm) is the EDFA output power per channel launched into the span, NF is the noise figure of the amplifier in dB, L_{span} is the product of the span loss in (dB), and N_{amp} is the number of spans. Equation (5.12) signifies that; increasing the EDFA output power, decreasing the noise figure, or reducing the span loss will increase the OSNR in a DWDM system.

However, increasing an EDFA output power will increase the noise figure, and four-wave mixing (Non-linear effect), since the four-wave mixing tends to increase with the square of the output power [3-5]. Furthermore, reducing the span loss will increase the system cost because it will require twice the number of EDFA in the DWDM system [91], [119], [120]. The OSNR must be kept high to achieve the required system performance, which is most often a bit-error rate (BER) of 10^{-12}. Since a BER is mathematically calculated by the use of Q, as in equation (5.11), Thus OSNR can be related to BER through Q by equation (5.13), as shown in [5].

$$Q_{dB} = OSNR_{dB} + 10\log\left(\frac{B_O}{B_E}\right) \tag{5.13}$$

Where B_O is the optical bandwidth of the receiver and B_E is the electrical bandwidth of the receiver post detection filter.

5.4. Performance of a DWDM system

The VPI TransmissionMaker DWDM (version 7.5) [126] has been used in this research to design and simulate the DWDM system for the deployment of the Tanzanian ICT backbone infrastructure. In this section we present simulation results, and analyse the DWDM system performance while taking into consideration the presence of each optical component individually, when data rates of 2.5 Gb/s and 10 Gb/s per wavelength channel are transmitted. Table 5.1 below provides parameters that are used to model various modules (optical components) in the DWDM system.

Parameter	Value	Module
Optical centre frequency	193.1 THz	Transmitter
Channel Spacing	100 GHz	" " "
Rise Time	1.0/4.0/Bit rate	" " "
Laser Average Power	1mW	" " "
Linewidth of the Laser	0.0 Hz	" " "
Responsivity	1 A/W	Receiver
Dark current	0.0 A	" " "
Avalance Multiplication	1.0	" " "
Ionization coefficient	1.0	" " "
Thermal Noise	3e-12 A/Hz	" " "
Bandwidth of Bessel Filter	0.7 * Bit rate	" " "
Output Power	1 W	EDFA
Gain	30 dB	" "
Gain Max	100 dB	" "
Gain Tilt	0 dB	" "
Noise Figure	6.0 dB	" "
Noise Bandwidth	0.0 Hz	" "
Noise Center Frequency	193.1 THz	" "
Multiplex Loss	6.0 dB	OXC/ROADM
Demux Loss	10.0 dB	" " "
Channel power in OXC/ROADM	3 W	" " "
Dispersion in SSMF	17 ps/nm	SSMF
Attenuation in SSMF	0.2 e-3	" "
Dispersion slope	0.08 e-3 s/m^2	" "
SSMF core Area	80 e-12 m^2	" "
Dispersion DCF	-90 e-6	" "
Attenuation DCF	0.8 e-3	" "

Table 5.1: Parameter for modelling DWDM system components

The eye diagram is used in the simulation of the DWDM system to determine the quality of the electrical signal at the receiver. In this regard, Figures 5.1 to 5.4 shows the simulation results when a data rate of 2.5 Gb/s is transmitted with a direct modulation and an external modulator transmitter over a distance of 120 km in the DWDM system without the utilisation of an erbium-doped fibre amplifier (EDFA) and a dispersion compensating fibre (DCF) in a SSMF. By using a direct modulation transmitter, simulation results (Figures 5.1 and 5.2) show that the signal eye is not completely open and the receiver sensitivity doesn't achieve the required BER of 10^{-12} for a good DWDM system performance due to the system impairment effects in a SSMF. However with an external modulator transmitter, (Figures 5.3 and 5.4) the simulation results show that the signal eye is open and the receiver sensitivity of 26.7 dBm achieves the required BER of 10^{-12} delivering good DWDM system performance.

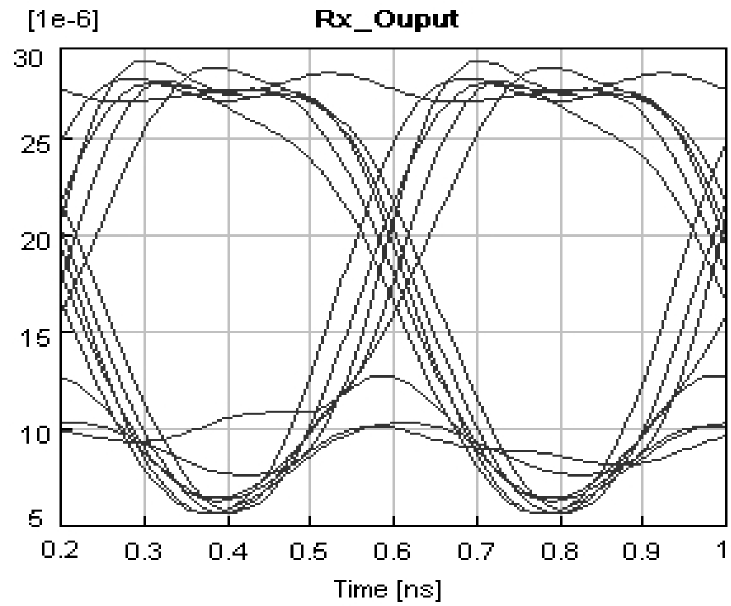

Figure 5.1: Eye diagram for 2.5 Gb/s (a direct modulation transmitter, 120 km distance)

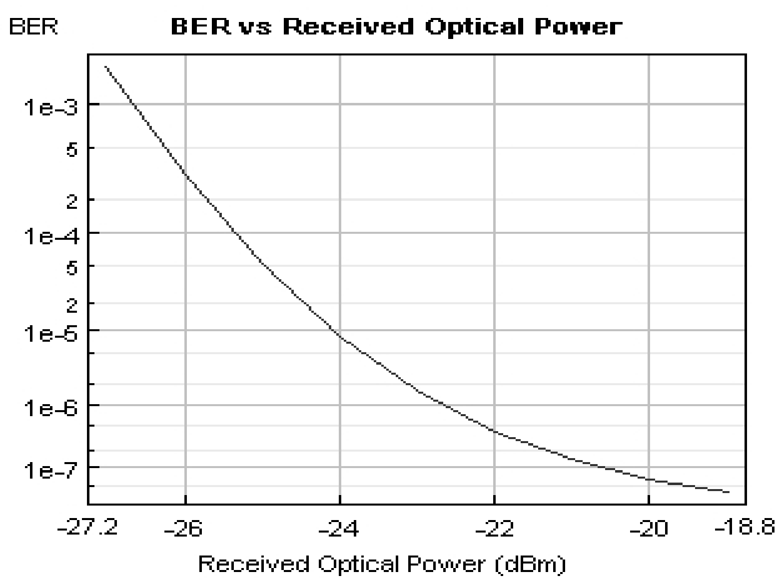

Figure 5.2: Receiver sensitivity for 2.5 Gb/s (a direct modulation transmitter, 120 km distance)

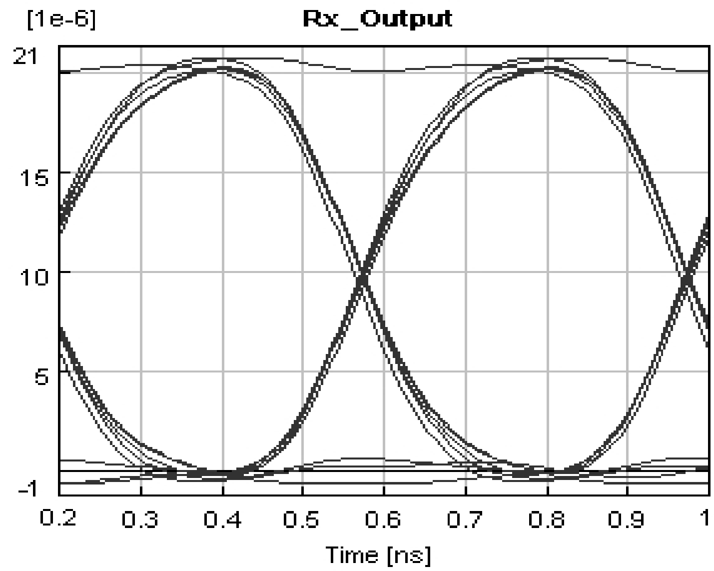

Figure 5.3: Eye diagram for 2.5 Gb/s (an external modulator transmitter, 120 km distance)

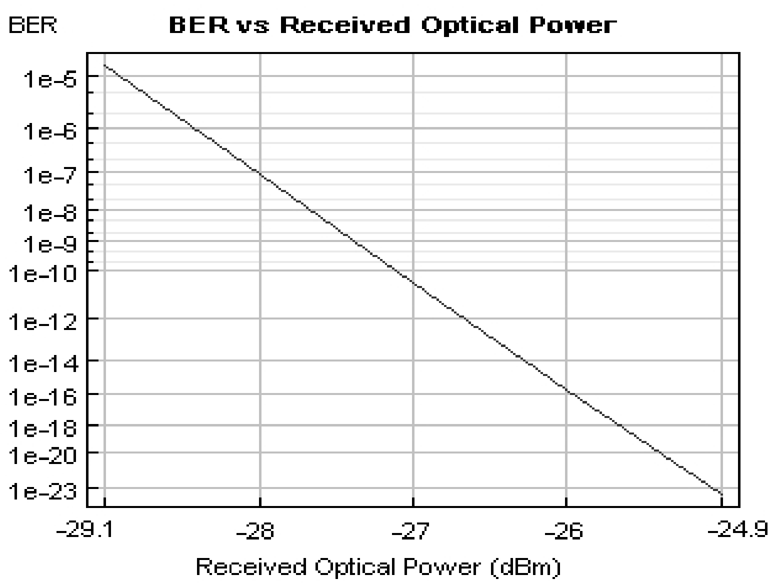

Figure 5.4: Receiver sensitivity for 2.5 Gb/s (an external modulator transmitter, 120 km distance)

Figures 5.5 to 5.8 show the simulation results when a data rate of 10 Gb/s is transmitted with direct modulation and an external modulator transmitter over a distance of 120 km in the DWDM system, also without the utilisation of an EDFA and a DCF in a SSMF. When using a direct modulation transmitter, simulation results show (Figures 5.5 and 5.6) that the signal eye is completely closed and the receiver sensitivity doesn't achieve the required BER value due to system impairment effects in a SSMF; hence a direct modulation transmitter is impractical for use in the DWDM system for a data transmission rate of either 2.5 Gb/s or 10 Gb/s. However with an external modulator transmitter, the simulation results show (Figures 5.7 and 5.8) that the signal eye is open and the receiver sensitivity of 22.6 dBm achieves the required BER of 10^{-12}. Therefore a transmitter with an external modulator provides good DWDM system performance for both data rates in contrast to a direct modulation transmitter.

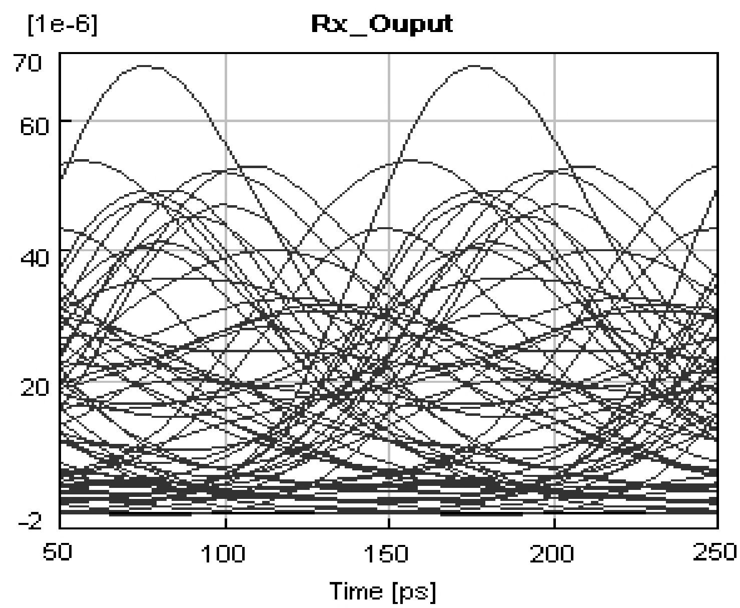

Figure 5.5: Eye diagram for 10 Gb/s (a direct modulation transmitter, 120 km distance)

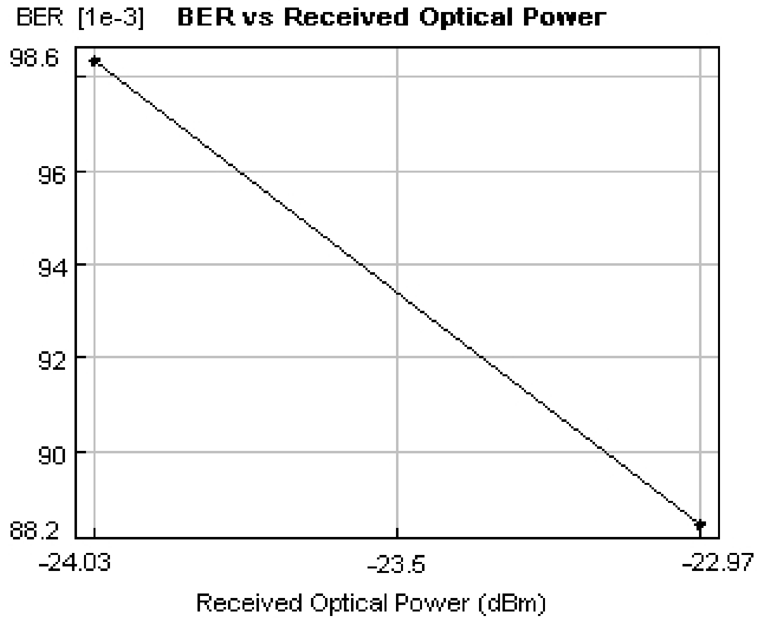

Figure 5.6: Receiver sensitivity for 10 Gb/s (a direct modulation transmitter, 120 km distance)

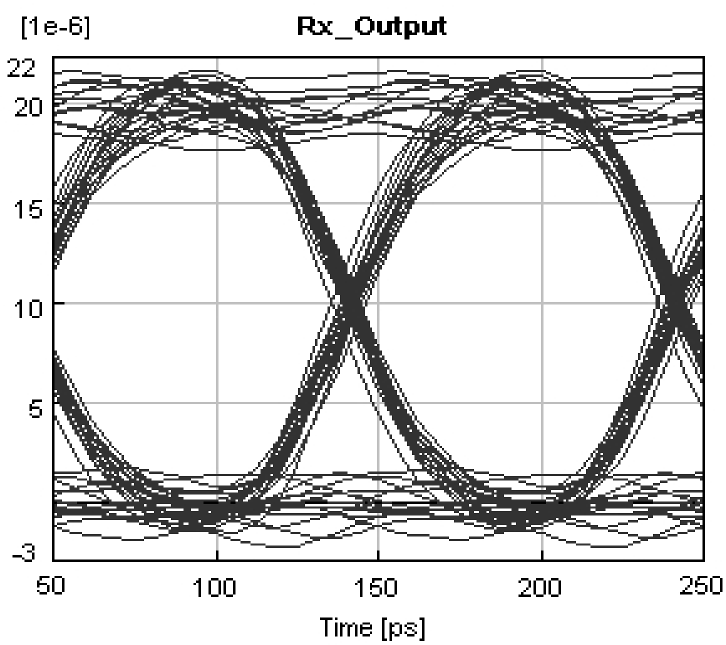

Figure 5.7: Eye diagram for 10 Gb/s (an external modulator transmitter, 120 km distance)

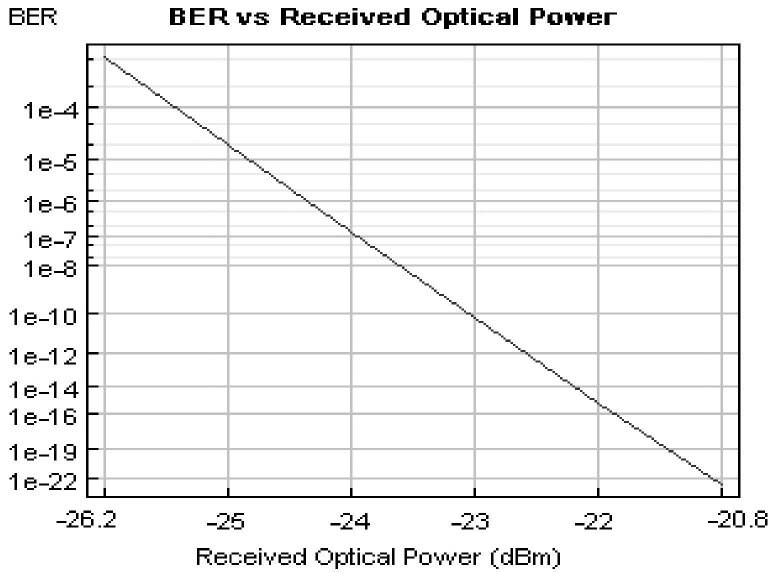

Figure 5.8: Receiver sensitivity for 10 Gb/s (an external modulator transmitter, 120 km distance)

Figures 5.9 to 5.12 show the simulation results when 2.5 Gb/s and 10 Gb/s data rates are transmitted with an external modulator transmitter over a distance of 130 km without utilizing an EDFA and a DCF in a SSMF. The simulation results for a data rate of 10 Gb/s show (Figures 5.9 and 5.10) that the signal eye is closed and the receiver sensitivity doesn't achieve the required BER of 10^{-12}. Also, the simulation results for data rate of 2.5 Gb/s show (Figures 5.11 and 5.12) that the signal eye is not completely open and the receiver sensitivity doesn't achieve the required BER of 10^{-12}. Therefore, simulation results for both data rates signify that the DWDM system performance is not good due to the system impairment effects in a SSMF. For this reason it is impractical to use an external transmitter modulator for a distance greater than 120 km to transmit data rates of 2.5 Gb/s or 10 Gb/s without the tilization of an EDFA and a DCF in a SSMF.

Hence, EDFA's (incorporating a DCF's) were inserted at each end of the SSMF, of 120 km span length, to compensate for signal power loss due to the system impairment effects. With this modification further analysis was carried out using the transmission rates of 2.5 Gb/s and 10 Gb/s with an external transmitter modulator to a SSMF 600 km long, which is the maximum distance between two adjacent nodes in the DWDM ring system.

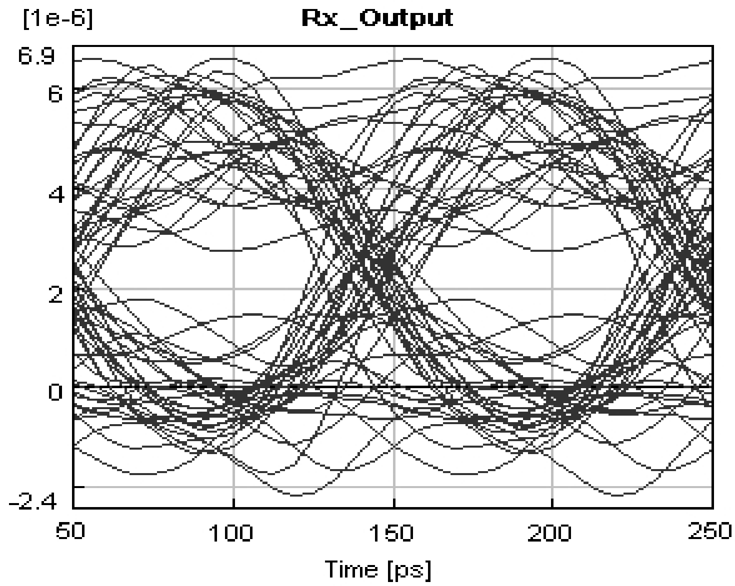

Figure 5.9: Eye diagram for 10 Gb/s (an external modulator transmitter, 130 km distance)

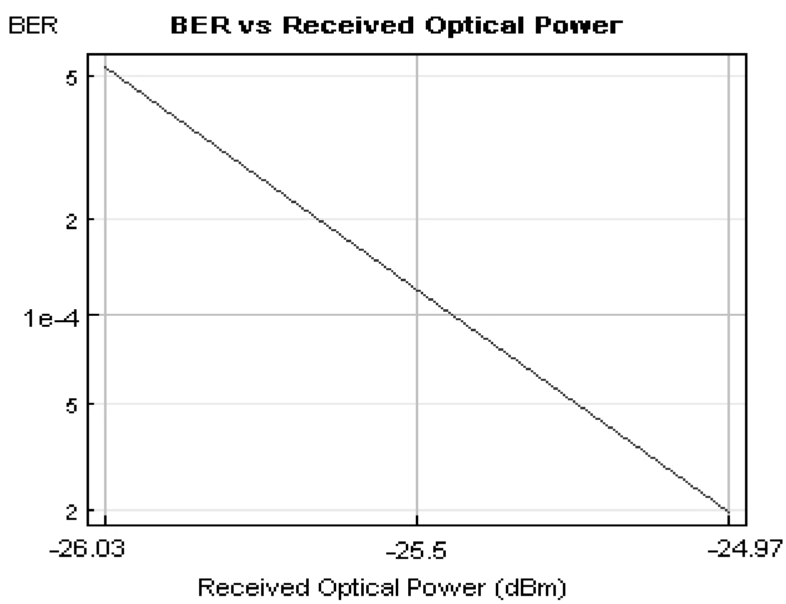

Figure 5.10: Receiver sensitivity for 10 Gb/s (an external modulator transmitter, 130 km distance)

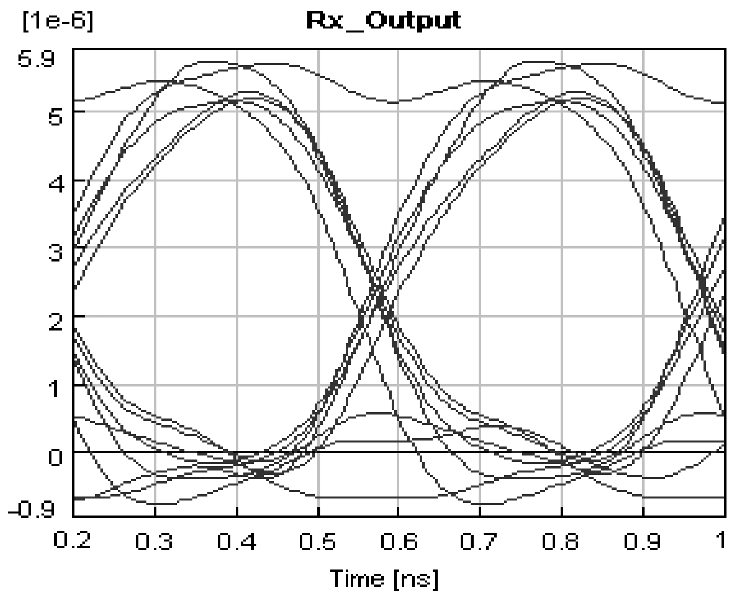

Figure 5.11: Eye diagram for 2.5 Gb/s (an external modulator transmitter, 130 km distance)

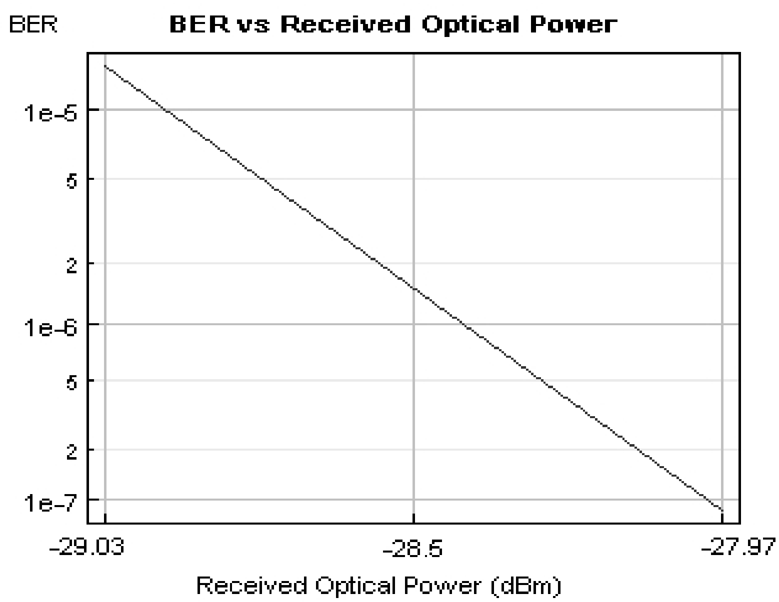

Figure 5.12: Receiver sensitivity for 2.5 Gb/s (an external modulation transmitter, 130 km distance)

The simulation results for a data rate of 2.5 Gb/s show (Figures 5.13 and 5.14) that the signal eye is open and the receiver sensitivity of 30.5 dBm achieves the required BER of 10^{-12} to deliver a good DWDM system performance. The simulation results for a data rate of 10 Gb/s, show that the signal eye is open and the receiver sensitivity of 25.9 dBm achieves the required BER of 10^{-12}, see Figures 5.15 and 5.16 respectively. Furthermore, the simulation results of Figures 5.17 and 5.18, shows that the OSNR is approximately 39 dB and 22 dB for the transmission of 2.5 Gb/s and 10 Gb/s respectively, with a span length of 120 km between an EDFA (incorporating a DCF) along 600 km distance between two adjacent nodes in the DWDM ring system; this is high and sufficient for good DWDM system performance.

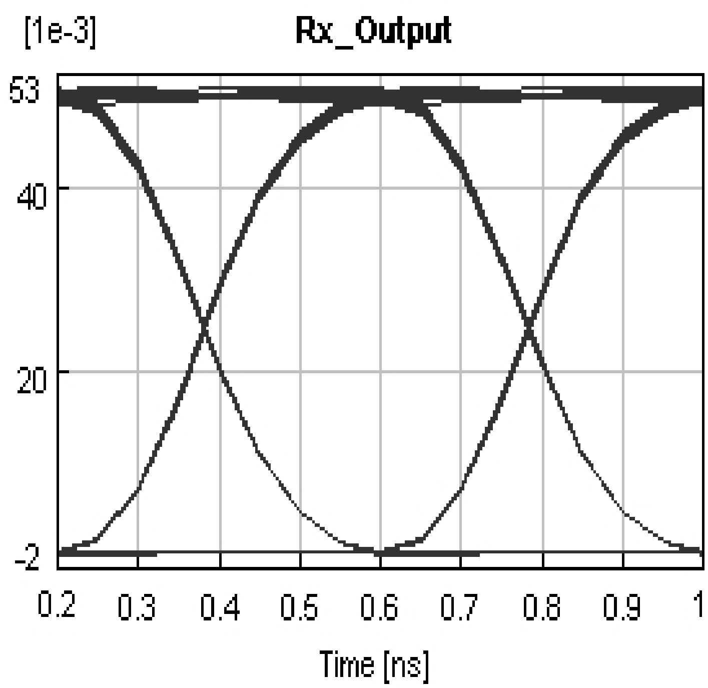

Figure 5.13: Eye diagram for 2.5 Gb/s, an external modulator transmitter with an EDFA (incorporating a DCF) inserted 120 km span along SSMF 600km distance

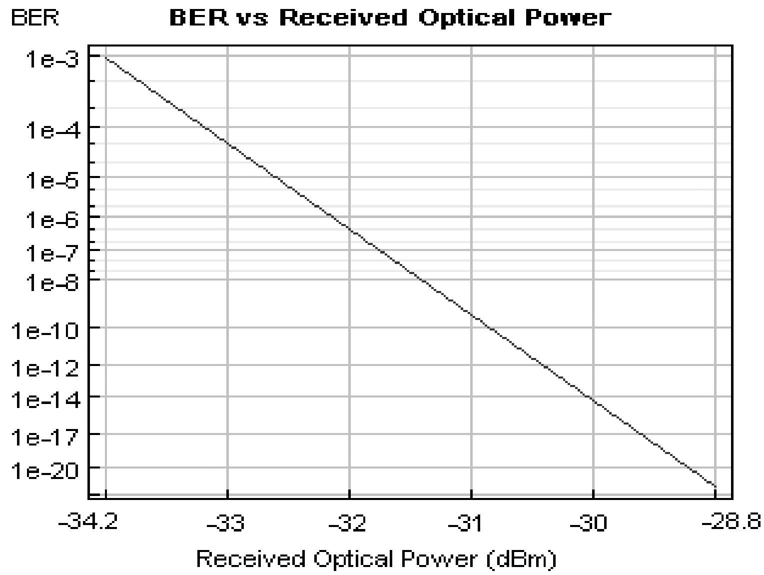

Figure 5.14: Receiver Sensitivity for 2.5 Gb/s, an external modulator transmitter with an EDFA (incorporating a DCF) inserted 120 km span along SSMF 600 km distance

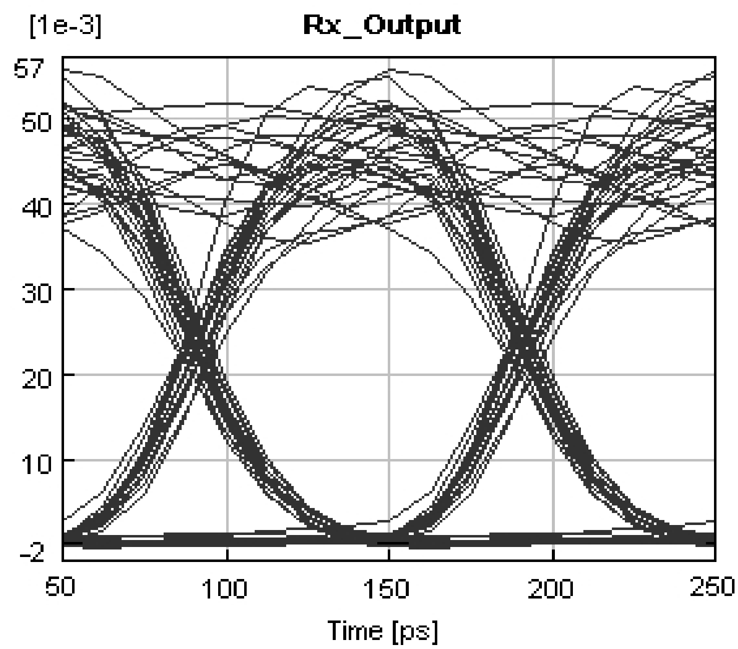

Figure 5.15: Eye diagram for 10 Gb/s, an external modulator transmitter with an EDFA (incorporating a DCF) inserted 120 km span along SSMF 600 km distance

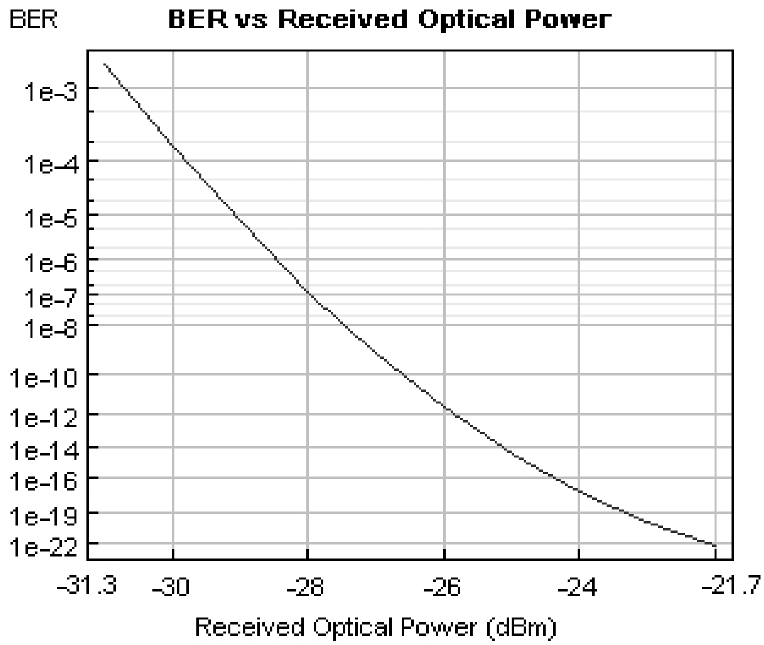

Figure 5.16: Receiver Sensitivity for 10 Gb/s, an external modulator transmitter with an EDFA (incorporating a DCF) inserted 120 km span along SSMF 600 km distance

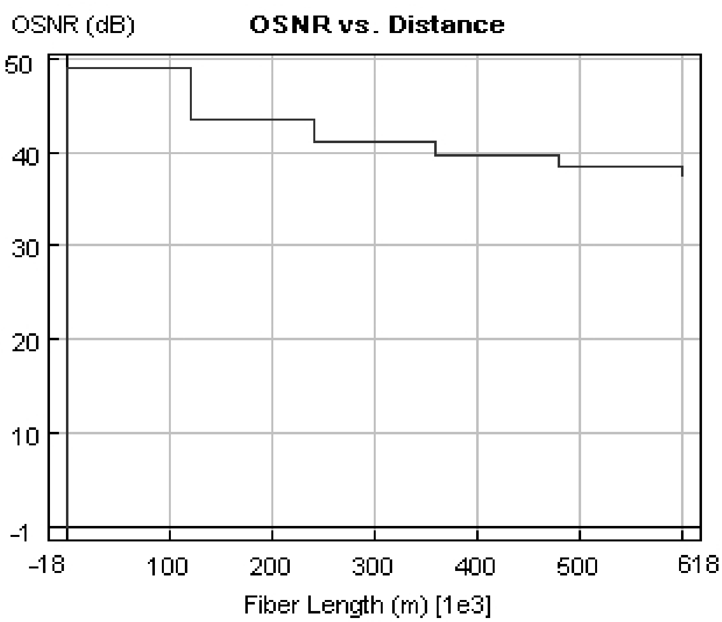

Figure 5.17: OSNR for 2.5 Gb/s vs. Distance, an external modulator transmitter with an EDFA (incorporating a DCF) inserted 120 km span along SSMF 600 km distance

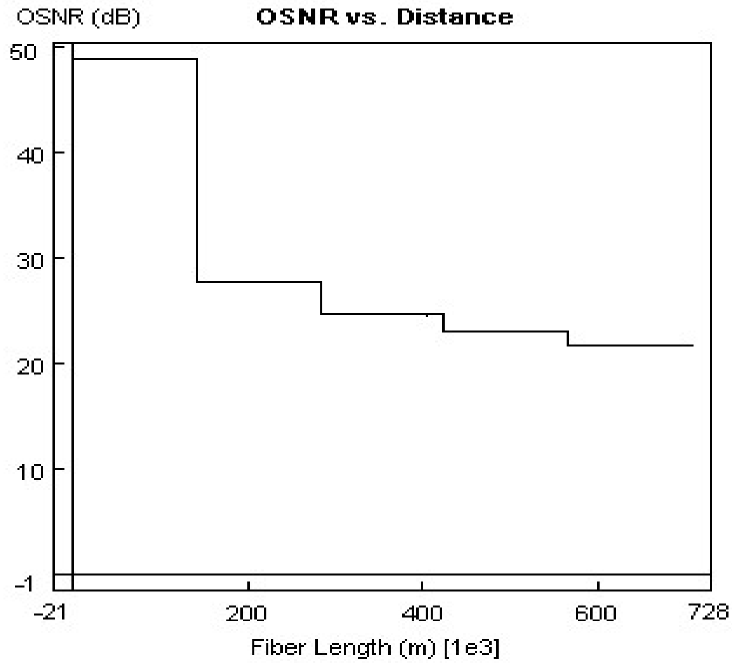

Figure 5.18: OSNR for 10 Gb/s vs. Distance, an external modulator transmitter with an EDFA (incorporating a DCF) inserted 120 km span along SSMF 600 km distance

When 2.5 Gb/s (see appendix 5) and 10 Gb/s (see appendix 6) data rates are transmitted with an external transmitter modulator over a distance of 3000 km (the estimated maximum length of DWDM system ring in Figure 4.2) with an EDFA (incorporating a DCF) inserted at each end of the SSMF with 120 km span length. The simulation results for a data rate of 2.5 Gb/s show (Figures 5.19 and 5.20) that the signal eye is open and the receiver sensitivity of 30.5 dBm achieves the required BER of 10^{-12} for a good DWDM system performance. However the simulation results for a data rate of 10 Gb/s show (Figures 5.21 and 5.22) the signal eye is closed and the receiver sensitivity doesn't achieve the required BER of 10^{-12}; this indicates poor DWDM system performance.

Furthermore, the simulation results of Figures 5.23 and 5.24, show the OSNR for data transmission rates of 2.5 Gb/s (see appendix 7) and 10 Gb/s (see appendix 8) respectively, with a span length of 120 km between an EDFA (incorporating a DCF) along the 3000 km distance between 2-nodes in a DWDM ring system. Figure 5.23 shows that for a data rate of 2.5 Gb/s, the OSNR is more than 30 dB (see appendix 7), which is high and sufficient for good DWDM system performance. While Figure 5.24 shows that for a data rate of 10 Gb/s, the OSNR is less than 10 dB (see appendix 8), which is insufficient for good DWDM system performance.

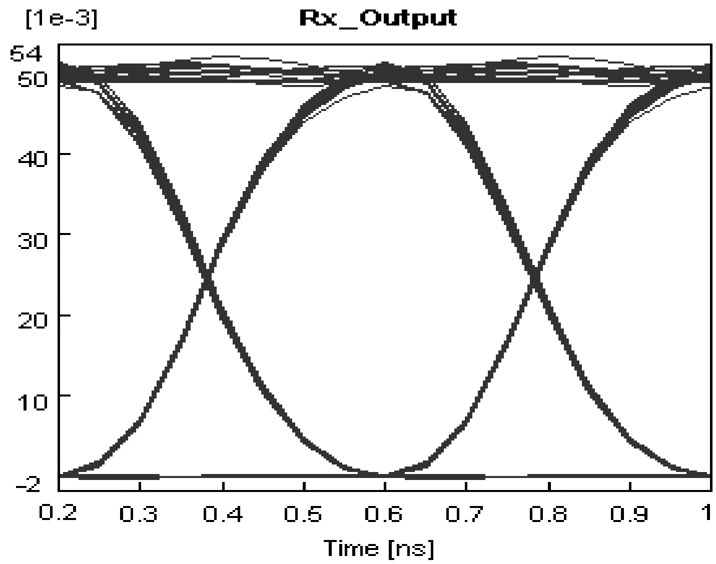

Figure 5.19: Eye diagram for 2.5 Gb/s, an external modulator transmitter with an EDFA (incorporating a DCF) inserted 120 km span along SSMF 3000 km distance

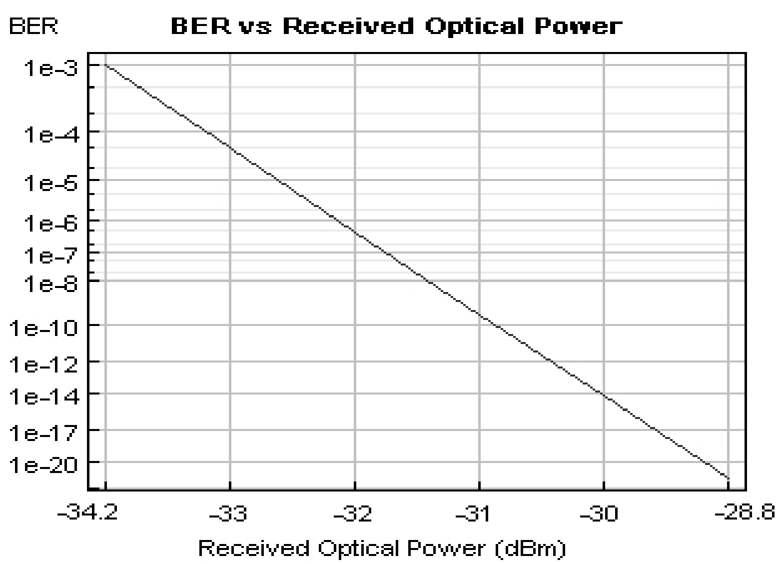

Figure 5.20: Receiver sensitivity for 2.5 Gb/s, an external modulator transmitter with an EDFA (incorporating a DCF) inserted 120 km span along SSMF 3000 km distance

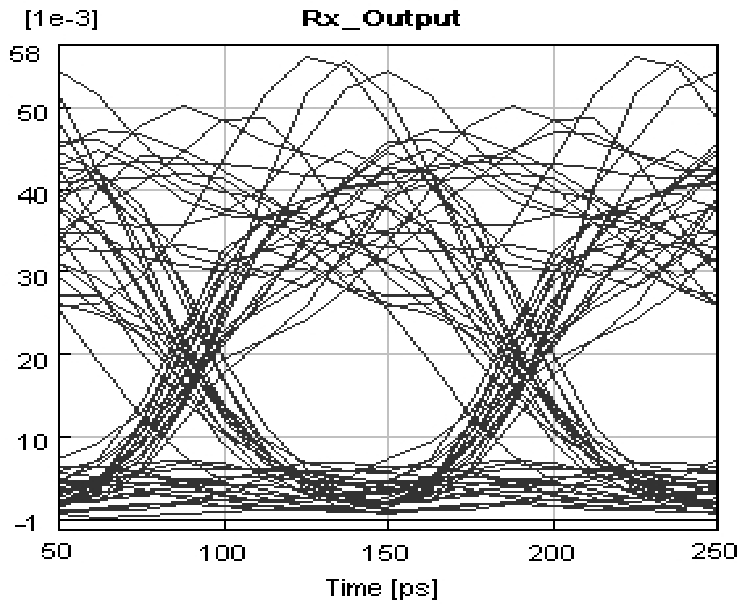

Figure 5.21: Eye diagram for 10 Gb/s, an external modulator transmitter with an EDFA (incorporating a DCF) inserted 120 km span along SSMF 3000 km distance

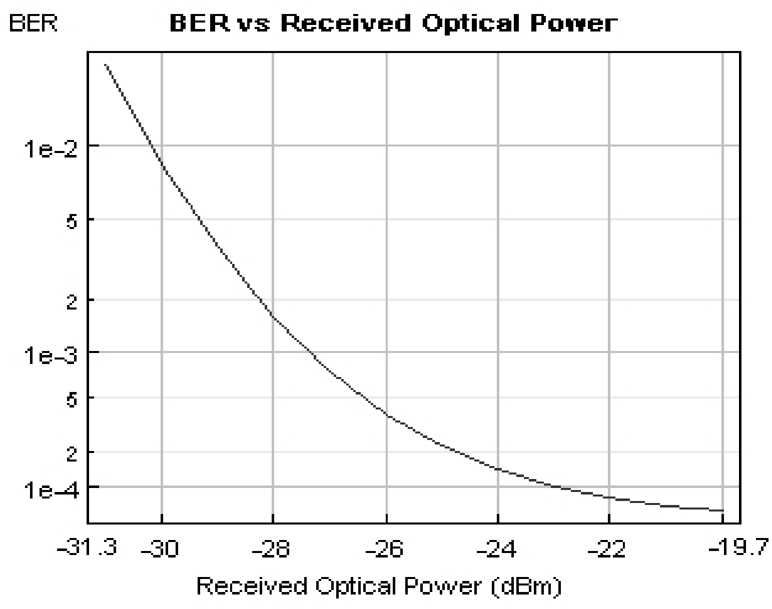

Figure 5.22: Receiver sensitivity for 10 Gb/s, an external modulator transmitter with an EDFA (incorporating a DCF) inserted 120 km span along SSMF 3000 km distance

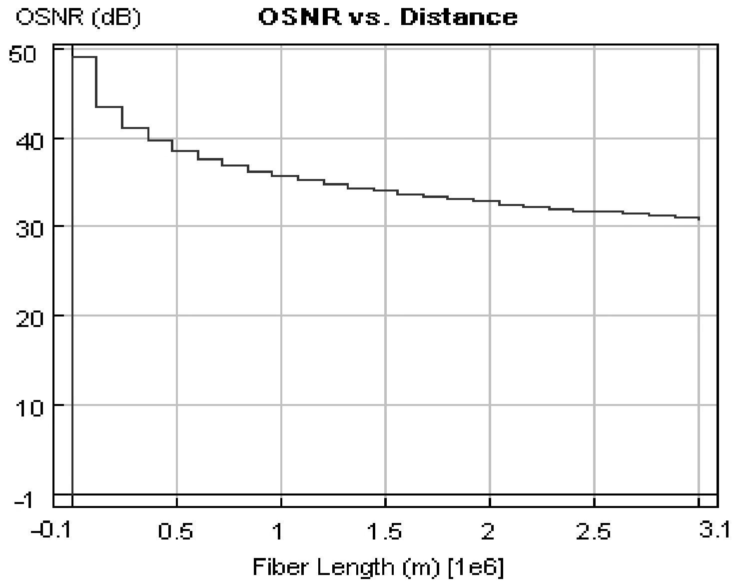

Figure 5.23: OSNR for 2.5 Gb/s vs. Distance, an external modulator transmitter with an EDFA (incorporating a DCF) inserted 120 km span along SSMF 3000 km distance

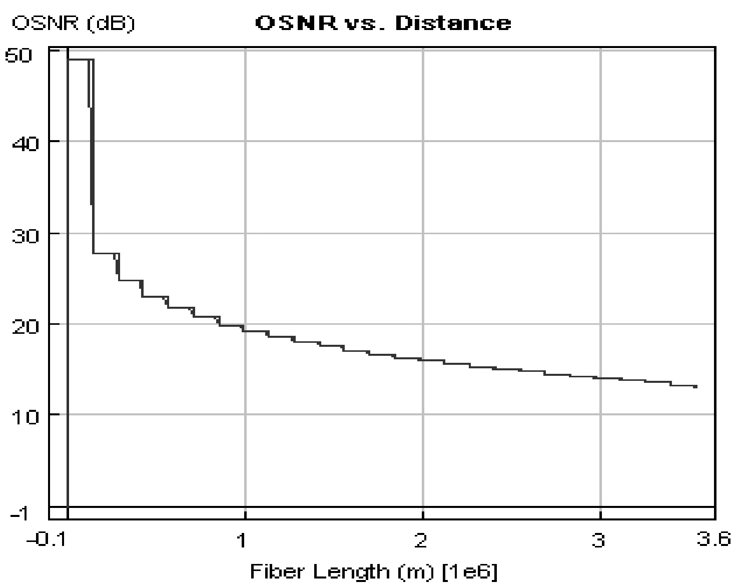

Figure 5.24: OSNR for 10 Gb/s vs. Distance, an external modulator transmitter with an EDFA (incorporating a DCF) inserted 120 km span along SSMF 3000 km distance

For this reason, further analysis was carried out to determine the maximum distance, which will provide good DWDM system performance with a data rate of 10 Gb/s with a span length of 120 km between 2-nodes in a DWDM ring system. The simulation results of Figures 5.25 and 5.26 respectively, show that the signal eye is open and the receiver sensitivity of 24.8 dBm achieves the required BER of 10^{-12} predicting a good DWDM system performance, and Figure 5.27 shows that the OSNR is approximately equal to 20 dB. When a data rate of 10 Gb/s is transmitted with an external transmitter modulator over the distance of 800 km, with a span length of 120 km between an EDFA (incorporating a DCF). This signifies that the receiver sensitivity of 24.8 dBm, and OSNR of 20 dB are the minimum limits for good DWDM system performance. Therefore, a data rate of 10 Gb/s with a span length of 120 km will be limited to the maximum distance of 800 km in a DWDM system due to system impairment effects in a SSMF.

However, when a span length of 120 km is reduced by 60 km distance between an EDFA (incorporating a DCF), a data rate of 10 Gb/s can be transmitted 3000 km in the DWDM ring system as shown in the simulation results of Figures 5.28 to 5.29. The simulation results of Figures 5.28 and 5.29 respectively, show that the signal eye is open and the receiver sensitivity of 27.4 dBm achieves the required BER of 10^{-12} for a good DWDM system performance, Figure 5.30 shows that the OSNR is approximately equal to 31 dB. Although this will increase the system costs because it will require twice the number of EDFAs (incorporating DCFs).

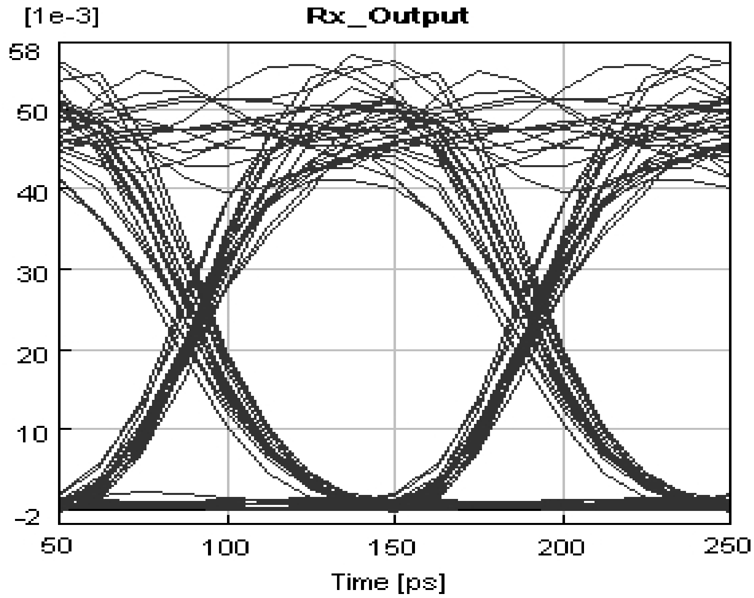

Figure 5.25: Eye diagram for 10 Gb/s, an external modulator transmitter with an EDFA (incorporating a DCF) inserted 120 km span along SSMF 800 km distance

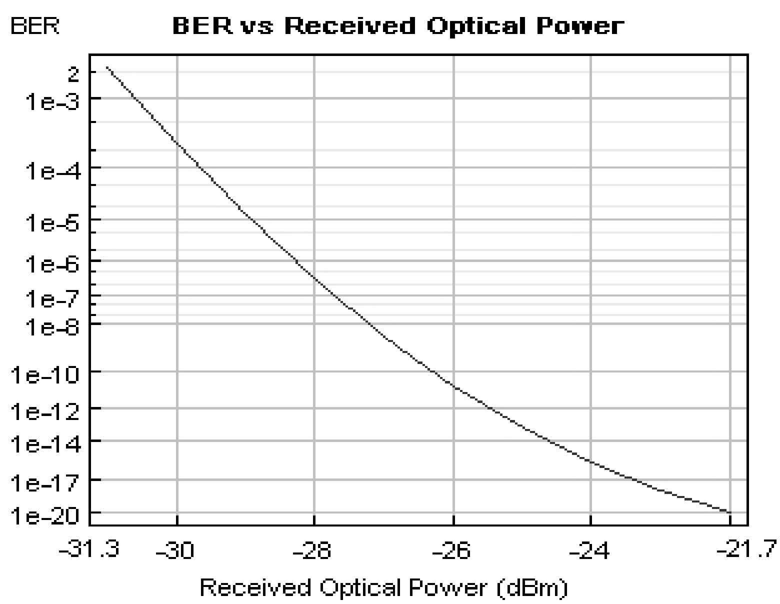

Figure 5.26: Receiver sensitivity for 10 Gb/s, an external modulator transmitter with an EDFA (incorporating a DCF) inserted 120 km span along SSMF 800 km distance

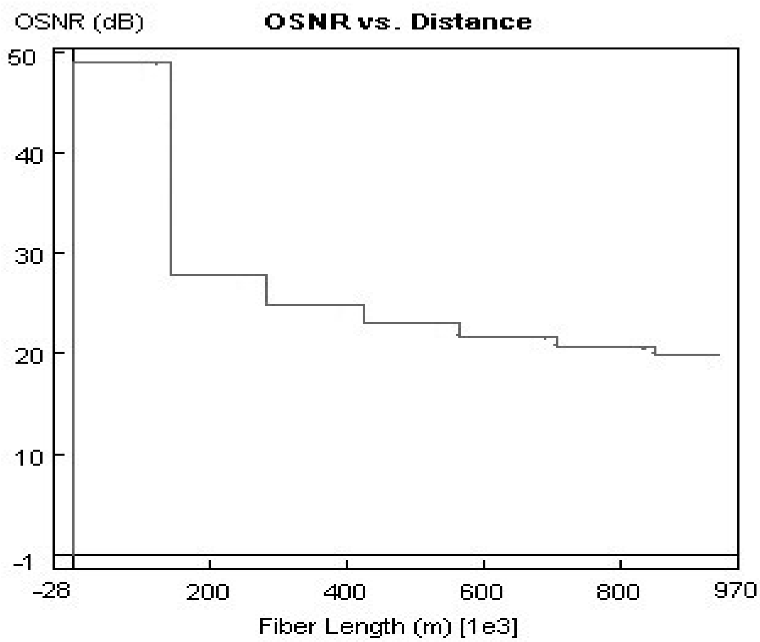

Figure 5.27: OSNR for 10 Gb/s vs. Distance, an external modulator transmitter with an EDFA (incorporating a DCF) inserted 120 km span along SSMF 800 km distance

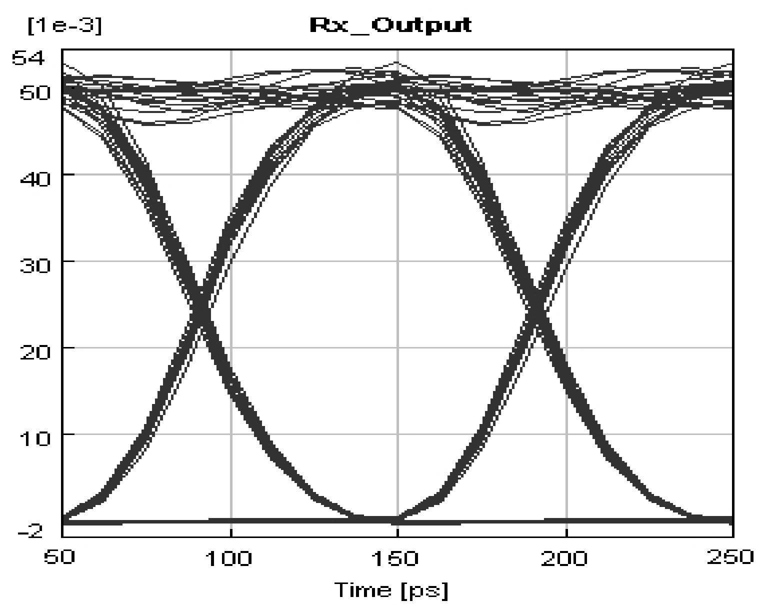

Figure 5.28: Eye diagram for 10 Gb/s, an external modulator transmitter with an EDFA (incorporating a DCF) inserted 60 km span along SSMF 3000 km distance

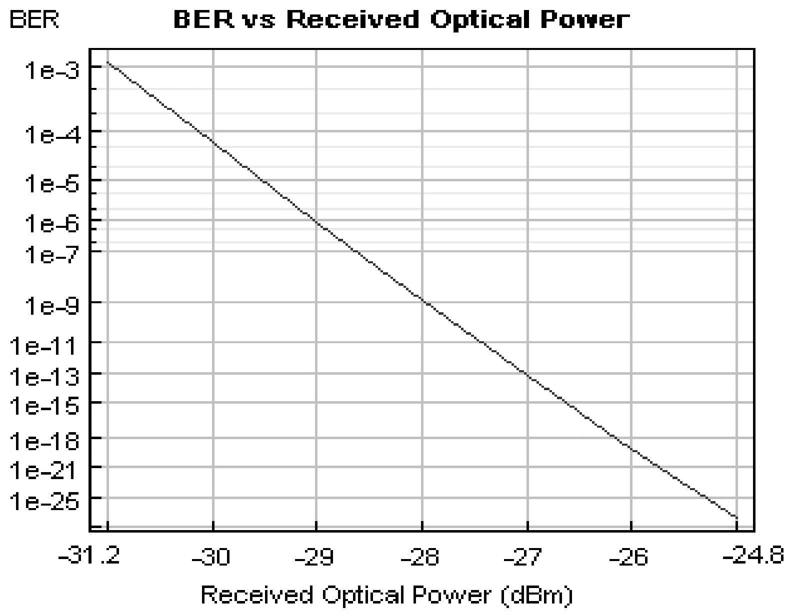

Figure 5.29: Receiver sensitivity for 10 Gb/s, an external modulator transmitter with an EDFA (incorporating a DCF) inserted 60 km span along SSMF 3000 km distance

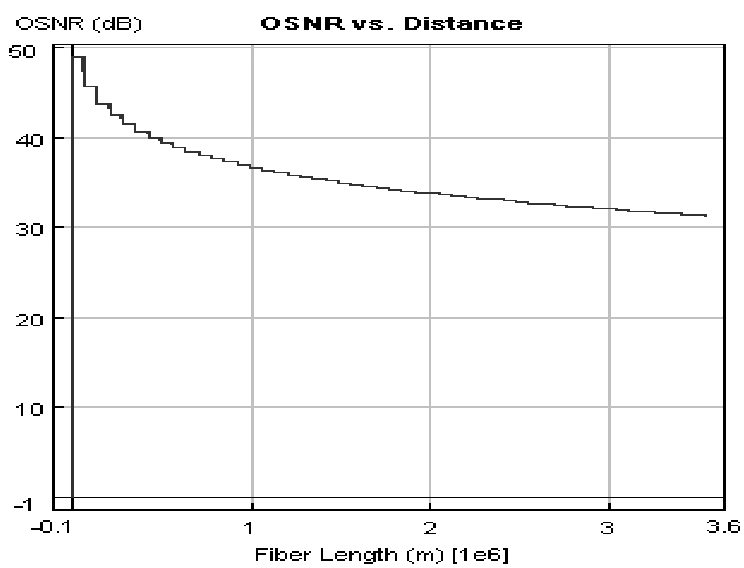

Figure 5.30: OSNR for 10 Gb/s vs. Distance, an external modulator transmitter with an EDFA (incorporating a DCF) inserted 60 km span along SSMF 3000 km distance

5.5. Conclusion

In this chapter we have demonstrated that to implement the optical DWDM network by using the existing standard single mode fibres (SSMFs), which are available in Tanzania, can limit the system performance especially when transmitting a data rate of 10 Gb/s or more due to the system impairment effects. As a result some compensation techniques must be used in order to reduce the system impairments in the DWDM systems. However most compensation will lead to more loss and high cost in the DWDM system. The simulation results show that a direct modulation transmitter is impractical for a transmission rate of either 2.5 Gb/s or 10 Gb/s data rates. It was also shown that, although an external modulator transmitter transmiting either 2.5 Gb/s or 10 Gb/s data rates in the DWDM system over a 120 km distance, it is still impractical when the distance exceeds 120 km without the installation of both an EDFA and a DCF in a standard single mode fibre (SSMF) due to the system impairment effects. However, when an erbium-doped fibre amplifier (EDFA) incorporating a dispersion compensating fibre (DCF) is installed at each end of a SSMF 120 km span, the simulation results show that a data rate of 2.5 Gb/s can be successfully transmitted with an external modulator transmitter over a distance of 3000 km without any system impairments in a SSMF, it also achieves the required BER of 10^{-12} to deliver good DWDM system performance. In contrast, a data rate of 10 Gb/s doesn't achieve the required BER of 10^{-12} due to system impairment affects, unless the span length of 120 km is reduced by half. This solution will increase the system costs because it will require twice the number of EDFAs (incorporating DCFs). Therefore, it is essential for a DWDM network in Tanzania to use only a data rate of 2.5 Gb/s per wavelength channel, which is adequate for good DWDM system performance, as we have seen in the simulation results. It is also sufficient to meet Internet traffic demand in Tanzania.

CHAPTER 6. COST ANALYSIS OF ICT BACKBONE INFRASTRUCTURE

6.1. Introduction

In this chapter, the cost analysis techniques demonstrated in [127-129] are used to justify the economic worth of incorporating existing SSMFs installations into an optical DWDM network for the creation of an affordable Tanzanian ICT backbone infrastructure; this approach is compared with building the ICT backbone infrastructure using a completely new SSMF DWDM network or a SONET/SDH network. The cost analysis deals with investment costs (capital and recurring costs) and revenues (benefit) for each network within its economic lifetime [130]. We estimate that the ICT backbone infrastructure will provide services to the majority of the people who live in urban and rural area for at least 10 years. The parameters taken for cost analysis (e.g. equipment costs, income tax, depreciation, salary, rent, utilities charges, tariffs, etc) are based on the current financial policies in Tanzania, the present situation of the country, and present ICT status of Tanzania [131], [132]. The economic measures of merit and sensitivity analysis for each network are presented in detail in section 6.5

6.2. Capital costs

The capital cost is the up-front investment cost for each network for the deployment of a Tanzanian ICT backbone infrastructure. This includes the costs of all DWDM and SONET/SDH network equipment deployed in the ICT backbone infrastructure. During the site survey of ICT status in Tanzania (chapter 3); sales and marketing officers from Tanzania Telecommunication company limited (TTCL), Tanzania-Zambia railway authority (TAZARA), Tanzania railway corporation (TRC), Tanzania electric supply company (TANESCO), Songo Songo gas supply (SONGAS), and Adwest communications (TZ) companies were interviewed so as to obtain the correct costs for each DWDM and SONET/SDH network. These companies own the existing SSMF, and also provide optical fibre communications services in Tanzania.

6.2.1. Capital costs for DWDM networks

According to the network topology illustrated in Figure 4.3; to deploy the Tanzanian ICT backbone infrastructure using a DWDM network technology a total SSMFs length of 8000 km will be needed, but as 4800 km is already available [119]. The total length of new SSMF, which needs to be added, is 3200 km long. The total number of erbium-doped fibre amplifiers (EDFAs) required is 56, which was estimated using the length of the DWDM ring. Four regenerators are used at each end of the DWDM system ring to regenerate the optical signal. The number of optical cross-connect switches (OXCs) (i.e. 9), Reconfigurable add/drop multiplexers (ROADMs) (i.e.12) and add/drop multiplexers (ADMs) (i.e. 34) are estimated from cities (nodes) in the network topology for the deployment of Tanzanian ICT backbone infrastructure (Figure 4.3).

The costs for the DWDM network equipment and the capital costs for both DWDM network (existing and completely newly built SSMF DWDM networks) are summarised in table 6.1. The capital cost to deploy a DWDM network with existing SSMF to meet the required ICT service demand for the majority of the people who live in urban and rural areas is \$59.1 millions. Figures 6.1 and 6.2 illustrate the capital cost breakdown in terms of DWDM network equipment. However, the capital cost to deploy the DWDM network with a completely newly built SSMF is \$120.6 millions. Figure 6.3 and 6.4 illustrates the capital cost breakdown in terms of DWDM network equipment for a newly built SSMF DWDM network. In Figure 6.1 to 6.4, both optical DWDM network signify that the greater percentage of the capital cost is for investment in the SSMFs as opposed to other DWDM network equipment. Since SSMFs are very expensive due to the high cost of installation (which is associated with acquiring the right of way, installation of the conduit and putting the SSMF in the conduit.

DWDM equipments	**Units**	**Units costs (USD) (Plus installation fees)**	**Total Units costs (USD)**
EDFA	56	82800 @56	4636800
Regenerators	4	178250 @4	713000
OXC	9	517500 @9	4657500
ROADM	12	437000 @12	5244000
ADM	34	86250 @34	2932500
(**A**). To deploy the infrastructure by the use of existing SSMFs	3200km(1x24 core)	12800 @3200	40960000
(**B**). To deploy the infrastructure by laying completely news SSMFs	8000km(1x24 core)	12800 @8000	102400000
	Total cost (**A**)		**59,143,800**
	Total costs (**B**)		**120,583,800**

Table 6.1: Capital costs for the DWDM network (Estimated in 2010)

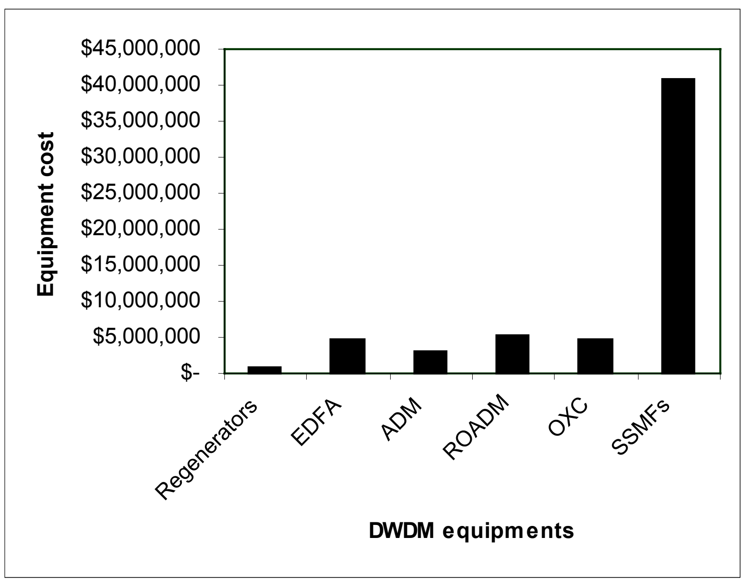

Figure 6.1: Capital breakdown cost for DWDM network with existing SSMFs

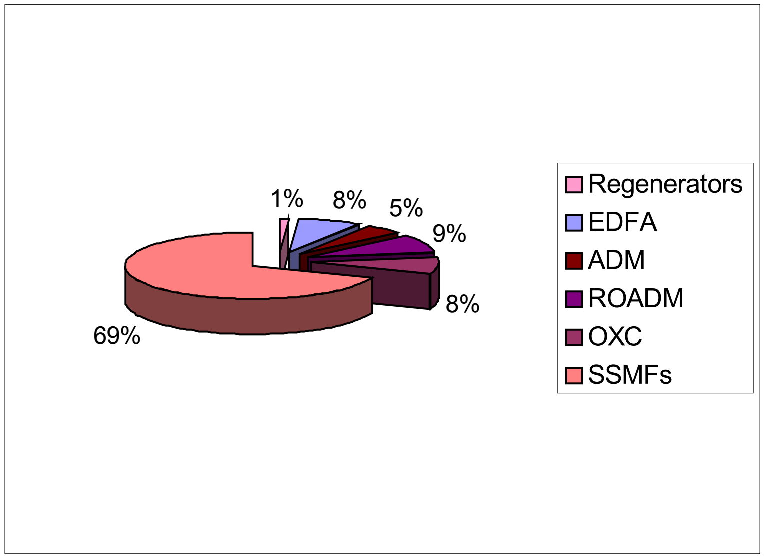

Figure 6.2: Capital breakdown percent for DWDM network with existing SSMFs

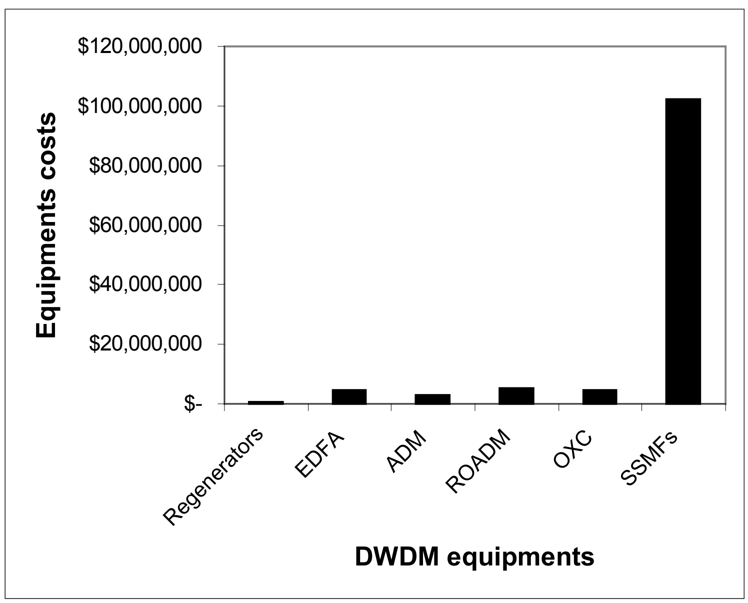

Figure 6.3: Capital breakdown cost for completely new built SSMFs DWDM network

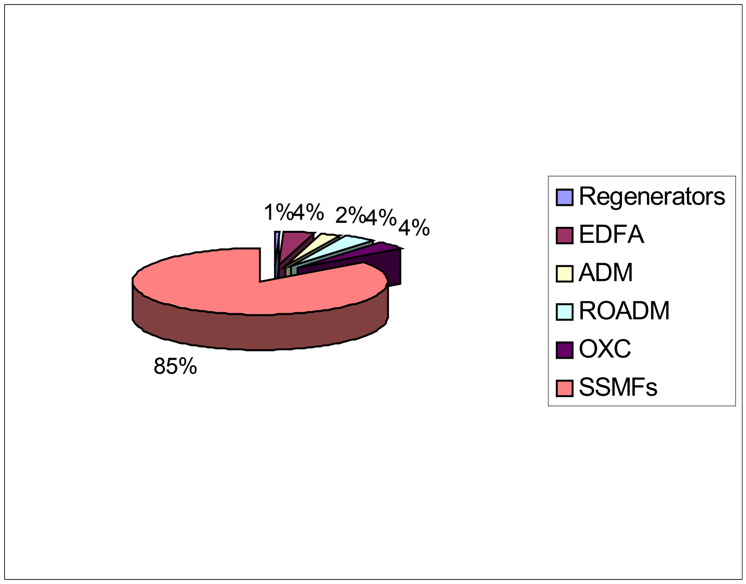

Figure 6.4: Capital breakdown percent for completely new built SSMFs DWDM network

6.2.2. Capital costs for SONET/SDH network

To deploy the ICT backbone infrastructure by the use of SONET/SDH network technology, the proposed network topology illustrated in (Figure 4.3) is used. Since each wavelength channel is achieved with one SSMF in a SONET/SDH network [4], [5]; hence multiple SSMF will be required to achieve the same capacity as in a DWDM network. Therefore 40 SSMF each carrying data rates of 2.5 Gb/s will be used to implement the ICT backbone infrastructure. As a result, the existing 4800 km of SSMF available will not be sufficient to implement the SONET/SDH network, since it has only 24 core fibres (1x24) SSMFs. Therefore a total length of SSMFs of 3200 km (1x24) and 8000 km (1x24) core fibres would need to be added to deploy a SONET/SDH network.

The total number of EDFAs is estimated to be 2240, which is calculated by multiplying the quantity of EDFAs (i.e. 56) by the number of SSMF's (i.e. 40). The regenerators are not required in a SONET/SDH network since at each node the optical signal is converted to electronic signal and back again to an optical signal for transmission on the SSMF. The numbers of digital circuit switches (DCS) and add/drop multiplexers (ADMs) are estimated from the quantity of network nodes (Cities) in Tanzania as illustrated in Figure 4.2. Each ADM in a SONET/SDH network handles one SSMF. Hence, we multiply the number of ADMs (i.e.13) in the node by the numbers of SSMF's (i.e. 40) to obtain the total quantity of ADMs (i.e. 520) in the SONET/SDH network. DCS can handle multiple SSMFs; thus only 9 are needed. The cost for every SONET/SDH network equipment and the capital costs are summarised in table 6.2. The capital cost to deploy a SONET/SDH network to meet the required ICT services demand for the majority of the people who live in urban and rural areas is $291.9 millions.

Figure 6.5 and 6.6 illustrate the capital cost breakdown in terms of SONET/SDH network equipment. Fig 6.7 illustrates a cost comparison between DWDM networks and a SONET/SDH network. Figure 6.7 shows that the capital costs of deploying a DWDM network is much less than a SONET/SDH network.

SONET/SDH equipments	**Unit**	**Unit costs (USD)**	**Total unit costs (USD)**
EDFA	2240	45,000 @ 2240	100800000
ADM	520	86,250 @ 520	44850000
EXM/DCS	9	320,000@ 9	2880000
Existing SSMFs	3200km (1x24)	12800 @ 3200	40960000
New SSMFs required	8000km (1x24)	12800 @ 8000	102400000
	Total cost		**291,890,000**

Table 6.2: Capital costs for the SONET/SDH network (Estimated in 2010)

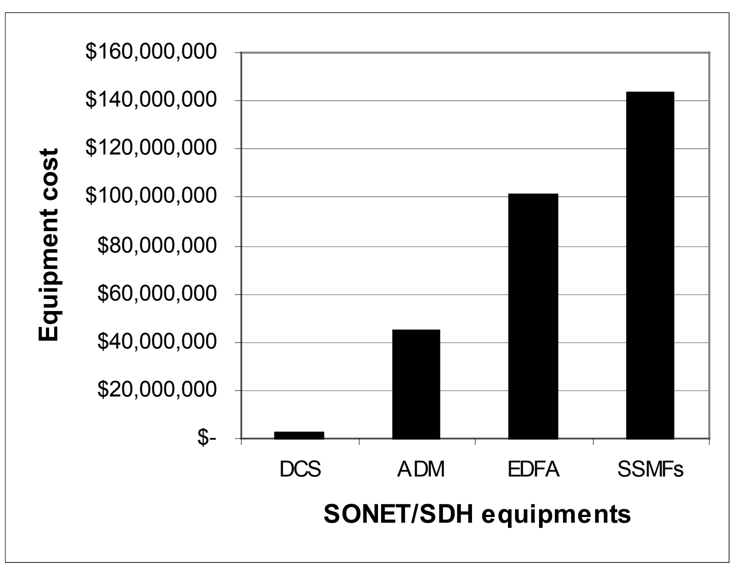

Figure 6.5: Capital breakdown cost for SONET/SDH network

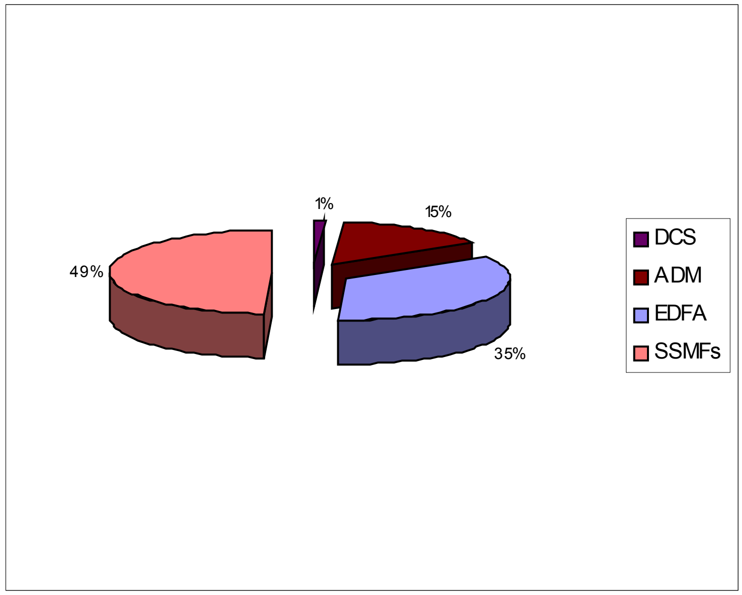

Figure 6.6: Capital breakdown percent for SONET/SDH network

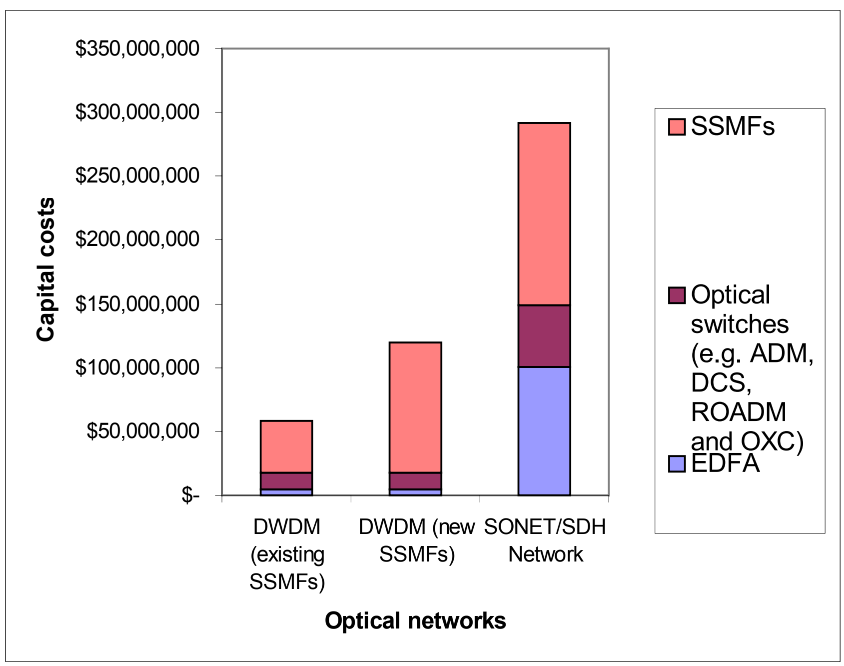

Figure 6.7: Cost distributions of optical networks

6.3. Recurring costs

Recurring costs (see table 6.3-6.5) represent the operational cost of maintaining and operating each network for the deployment of the Tanzanian ICT backbone infrastructure. As well as sales, marketing and administration costs.

6.3.1. Operational costs

The operational cost includes the following; the rent for ICT service provider offices across the country; the cost of electricity to provide power to the offices and cooling of the SSMF plant; the cost of software and replacing faulty DWDM and SONET/SDH network equipments which is due to the need to periodically update or repair equipment, and the salary of operations staff (i.e. Engineers and Technicians), which includes day-to-day operations, repair and also preventive maintenance.

6.3.2. Sales, marketing and administrative costs

These costs represent a substantial portion of overall costs. The amount of resources that a company puts into sales and marketing depends on how competitive the company is and what the company sales and marketing strategy is. Identifying ICT service providers or operators trends for sales and marketing is beyond the scope of this article. One approach to determine sales and marketing costs is to consider how much outsourcing this service would cost [134]. For example, sales and marketing people would take a certain percentage of revenue based on their commission contract. Administrative costs typically consist of the salaries for administrative, accounting, finance and other staff who are not in the operating department. Also, determining their costs is not as straight forward as determining the salaries of Engineers and Technicians. Therefore we quantify sales, marketing and administrative costs by basing them on a percentage of revenue. Hence, a default value of 20% of revenue is chosen to represent the sales, marketing and administrative costs.

Description	Value	Costs per annum (USD)
Offices rent for building and other utilities charges	$200000 per annum	200000
Average salaries for 120 employees of operation Dept.	$6000 per person per annum	72000
Costs for sales, marketing and administration	20 % of revenue	9680000
Software and replacing faulty equipments costs	3% of capital cost	1774314
Total Recurring costs		**12,374,314**

Table 6.3: Recurring costs for the DWDM network with existing SSMFs (Estimated in 2010)

Description	Value	Costs per year (USD)
Companies rent for building and other utilities charges	$200000 per year	200000
Average salaries for 120 employees of operation Dept.	$6000 per person per year	72000
Costs for sales, advertising, promotion & marketing plus salaries and commissions	20 % of revenue	9680000
Software and replacing new components costs	3% of capital investments	3617514
Total operating costs		**14,217,514**

Table 6.4: Recurring costs for a new built DWDM network (Estimated in 2010)

Description	Value	Costs per annum (USD)
Companies rent for building and other utilities charges	$200000 per year	200000
Average salaries for 120 employees of operation Dept.	$6000 per person per year	720000
Costs for sales, advertising, promotion & marketing plus salaries and commissions.	20 % of revenue	9680000
Software and replacing new components costs	3% of capital investments	8756700
Total Recurring costs		**19,356,700**

Table 6.5: Recurring costs for the SONET/SDH network (Estimated in 2010)

6.4. Revenues

Revenues are determined from selling home and commercial broadband services, and to provide ICT backbone infrastructure access and international connections (secondary markets) to other companies (see table 6.6).

6.4.1. Home broadband services

Home broadband is obtained after selling broadband to the users who access broadband services (i.e. High speed Internet access and landline telephone) from home. At present, the Internet penetration in Tanzania is only 1%; therefore we assumed only 0.2% of the population would receive home broadband after the ICT backbone infrastructure is established. This ratio will rise each year due to the larger number of people that can afford to pay the lower rates, and are also attracted to broadband services which will enable them to enjoy a fast internet connection (where they can also watch films and video online) and landline telephone in one package. At present, the Internet connection cost for a residential bandwidth of 60 Kb/s to 128 Kb/s is approximately $60 per month; therefore it will be replaced with a broadband line at an affordable cost of $30 per month.

6.4.2. Commercial broadband services

Commercial broadband is based on selling broadband services to private and government offices. Currently, the monthly charge for a commercial Internet bandwidth of 512 Kb/s is approximately $800. If we replaced it with a commercial broadband, we assume business customers will pay at least $400 per month (half the current rate) to access Internet service from the work place. We estimate 2000 organisations will purchase the commercial broadband once the ICT backbone infrastructure is established.

6.4.3. Secondary markets

The ICT backbone infrastructure will also provide backbone access and international connection to other ICT service providers (e.g. mobile and fixed telephone lines, multimedia companies and etc); we estimate that this will generate approximately $10 Millions per annum.

Description	ICT service charges	Total (USD)
Home broadband	$360 per household	28,800,000
Commercial broadband for the following organisation; Internet cafes; Government ministry & offices; Private & Government companies; industrial; Universities, Colleges and School, Banking and other organisation in Tanzania	$4800 per organisation office	9,600,000
Secondary market (provides backbone access and international connections to other telecommunication, mobile and multi-media companies in Tanzania)	Approximately $10 Millions	10,000,000
Total Revenues		**48,400,000**

Table 6.6: Revenues generated from the ICT backbone infrastructure (Estimated in 2010)

6.5. Economic measures of merit and Sensitivity analysis

This section provides economic measures of merit and sensitivity analysis for each network for the deployment of Tanzanian ICT backbone infrastructure. The economic measures of merit are based on net present value (NPV), present worth, payback time and internal rate of return (IRR). Sensitivity analysis is used to analyse uncertainties that may occur due to the input or output parameter changes in the ICT backbone infrastructure investment.

6.5.1. Net present value (NPV)

This economic measure of merit is used to determine the net present value of cash flows generated by both networks over the economic lifetime of the Tanzanian ICT backbone infrastructure. The cash flow is calculated by subtracting the total present worth of future net cash inflow (net operating profit) from the total cash outflow (e.g. capital plus recurring costs). Net cash inflow for each year is calculated after deduction of depreciation charges and net income taxes from the revenue for both networks (see table 6.7-6.9). Depreciation charges are calculated according to the straight-line method [127-129]. Income tax is charged at 30 percent of the revenues, according to the Tanzanian tax system [131]. Then the present worth of future net cash inflow is calculated using the formula shown in [127-129]. In order to estimate the appropriate values of present worth of future net cash inflows, we assume a discount factor of 10%, which is the industry benchmark rate-of-return.

Results for the DWDM network with existing SSMFs show that the net present value calculated is positive and the payback time is approximately 4 years (see table 6.10). This shows that the average annual cash return is 25 percent, which is excellent in terms of financial performance. The payback time is the number of years required to recover the capital cost of the ICT backbone infrastructure investment. In a completely new build SSMFs DWDM network, results show that the net present value calculated is also positive but the payback time is 8 years (see table 6.11). This shows that the average annual cash return is 12.6 percent, which is less than half, in terms of financial performance, compared to the DWDM network using the existing SSMFs. However, for the SONET/SDH network, results show that the net present value calculated is negative and the payback time is 12 years (see table 6.12), which is more than its economic lifetime. Also, the average annual cash return is 8%, which is very poor in terms of financial performance.

Year	**Investment costs**	**Net income before taxes depreciation charge**	**Depreciation charge**	**Net taxable income**	**30% of net income taxes**	**Net income after taxes**	**Net cash flow**
2010	71518114	0	0	0	0	0	0
2011		48400000	5914380	42485620	12745686	29739934	18660066
2012		53240000	5914380	47325620	14197686	33127934	20112066
2013		58564000	5914380	52649620	15794886	36854734	21709266
2014		64420400	5914380	58506020	17551806	40954214	23466186
2015		70862440	5914380	64948060	19484418	45463642	25398798
2016		77948684	5914380	72034304	21610291	50424013	27524671
2017		85743552	5914380	79829172	23948752	55880420	29863132
2018		94317907	5914380	88403527	26521058	61882469	32435438
2019		103749698	5914380	97835318	29350595	68484723	35264975
2020		114124668	5914380	108210288	32463086	75747202	38377466

Table 6.7: Financial summary for the DWDM Network with existing SSMFs

Year	Investment costs	Net income before taxes depreciation charge	Depreciation charge	Net taxable income	30% of net income taxes	Net income after taxes	Net cash flow
2010	134801314	0	0	0	0	0	0
2011		48400000	12058380	36341620	10902486	25439134	22960866
2012		53240000	12058380	41181620	12354486	28827134	24412866
2013		58564000	12058380	46505620	13951686	32553934	26010066
2014		64420400	12058380	52362020	15708606	36653414	27766986
2015		70862440	12058380	58804060	17641218	41162842	29699598
2016		77948684	12058380	65890304	19767091	46123213	31825471
2017		85743552	12058380	73685172	22105552	51579620	34163932
2018		94317907	12058380	82259527	24677858	57581669	36736238
2019		103749698	12058380	91691318	27507395	64183923	39565775
2020		114124668	12058380	102066288	30619886	71446402	42678266

Table 6.8: Financial summary for the DWDM Network with completely new SSMFs

Year	Investment costs	Net income before taxes depreciation charge	Depreciation charge	Net taxable income	30% of net income taxes	Net income after taxes	Net cash flow
2010	311246700	0	0	0	0	0	0
2011		48400000	31124670	17275330	5182599	12092731	36307269
2012		53240000	31124670	22115330	6634599	15480731	37759269
2013		58564000	31124670	27439330	8231799	19207531	39356469
2014		64420400	31124670	33295730	9888719	23307011	41113389
2015		70862440	31124670	39737770	11921331	27816439	43046001
2016		77948684	31124670	46824014	14047204	32776810	45171874
2017		85743552	31124670	54618882	16385665	38233217	47510335
2018		94317907	31124670	63193237	18957971	44235266	50082641
2019		103749698	31124670	72625028	21787508	50837520	52912178
2020		114124668	31124670	82999998	24899999	58099999	56024669
2021		125537135	31124670	94412465	2832740	66088726	59448410
2022		138090848	31124670	106966178	32089853	74876325	63214523

Table 6.9: Financial summary for the SONET/SDH network

Year	Net cash flow	Cumulative cash flow	Net cash flow DCF at 10%	Cumulative DCF at 10%	Net cash flow DCF at 30%	Cumulative DCF at 30%
2010	71518114	-71518114	71518114	-71518114	71518114	-71518114
2011	18660066	-52858048	16963696	-60694418	14353897	-57164217
2012	20112066	-32745982	16621542	-44072876	11900631	-45263586
2013	21709266	-11036716	16322756	-27750120	9881323	-35382263
2014	23466186	+12429470	16072730	-11677390	8216452	-27165811
2015	25398798	+37828268	15874249	+4196859	6840690	-20325121
2016	27524671	+65352939	15550662	+19747521	5702468	-14622653
2017	29863132	+95216071	15393367	+35140888	4759065	-9863588
2018	32435438	+127651509	15156747	+50297635	3976393	-5887195
2019	35264975	+162916484	14942786	+65240421	3326884	-2560311
2020	38377466	+201293950	14817554	+80057975	2784002	+223691

Table 6.10: Cash flow summary for the DWDM Network with existing SSMFs

Year	Net cash flow	Cumulative cash flow	Net cash flow DCF at 10%	Cumulative DCF at 10%	Net cash flow DCF at 17%	Cumulative DCF at 17%
2010	134801314	-134801314	134801314	-134801314	134801314	-134801314
2011	22960866	-111840448	20873515	-113927799	19624672	-115176642
2012	24412866	-87427582	20175922	-93751877	17832626	-97344016
2013	26010066	-61417516	19556441	-74195436	16256291	-81087725
2014	27766986	-33650530	19018484	-55176952	14848656	-66239069
2015	29699598	-3950932	18562249	-36614703	13561460	-52677609
2016	31825471	+27874539	17980492	-18634211	12431825	-40245784
2017	34163932	+62038471	17610274	-1023937	11387977	-28857807
2018	36736238	+98774709	17166466	+16142529	10466165	-18391642
2019	39565775	+138340484	16765159	+32907688	9603343	-8788299
2020	42678266	+181018750	16478095	+49385783	8891305	+103006

Table 6.11: Cash flow summary for the DWDM Network with completely new SSMFs

Year	Net cash flow	Cumulative cash flow	Net cash flow DCF at 10%	Cumulative DCF at 10%	Net cash flow DCF at 7%	Cumulative DCF at 7%
2010	311246700	-311246700	311246700	-311246700	311246700	-311246700
2011	36307269	-274939431	33006608	-278240092	33932027	-277314673
2012	37759269	-237180162	31206007	-247034085	32834147	-244480526
2013	39356469	-197823693	29591330	-217442755	31997129	-212483397
2014	41113389	-156710304	28159856	-189282899	31384266	-181099131
2015	43046001	-113664303	26903751	-162379148	30747143	-150351988
2016	45171874	-68492429	25520833	-136858315	30114583	-120237405
2017	47510335	-20982094	24489863	-112368452	29509525	-90727880
2018	50082641	+29100547	23403103	-88965349	29117815	-61610065
2019	52912178	+82012725	22420414	-66544935	28756618	-32853447
2020	56024669	+138037394	21631146	-44913789	28438918	-4414529
2021	59448410	+197485804	20837157	-24076632	28174602	+23760073
2022	63214523	+260700327	20144845	-3931787	28095344	+51855417

Table 6.12: Cash flow summary for the SONET/SDH network

6.5.2. Internal rate of return (IRR)

This measures the maximum interest rate, which the ICT service provider would be prepared to pay on money (i.e. capital cost) borrowed for the 10-year project lifetime. It is a special case of the present worth method, in which the sum of the present worth of all costs (i.e. capital plus recurring costs) and revenue generated for 10 years is set equal to zero. By using trial-and-error techniques [127], [128], we determined that the internal rate of return (IRR) for the DWDM network with existing SSMFs is 30%, which is higher than the industry benchmark rate-of-return. According to the above economic measure of merit, the IRR shows that even when the DWDM network investment uses a high interest rate of 30%, the financial profit will still be good, and the payback time is 10 years (see table 6.10 above), this delivers an average annual cash return of 11 percent.

However, in a completely new SSMFs DWDM network the IRR and payback time are 17% and 10 years respectively (see table 6.11 above), which signify that the ICT service provider has to use a lower IRR rate of not more than 17% to pay off the capital costs within its economic life, otherwise it will operate in debt. For the SONET/SDH Network, the IRR and payback time are 7% and 10 years respectively (see table 6.12 above). As a result, a SONET/SDH network will need more than its economic lifetime to repay its investment costs unless the IRR is reduced to the lower value of 7% or less. This signifies that it would be imprudent to develop the ICT backbone infrastructure using a SONET/SDH network. However, both DWDM network investments, especially making use of existing SSMFs, show a potential financial profit for its deployment.

6.5.3. Sensitivity analysis

This is defined as the change in output brought about by a specified change in input. The main purpose of sensitivity analysis is to determine which of several inputs may be the most important and to what extent, each input will affect the output parameters. During the preliminary stages of ICT backbone infrastructure planning there were many uncertainties, which were often difficult to define, given the changing conditions under which both networks would operate. For example, Pre-design estimates of capital costs might be inaccurate by as much as 30 percent or estimates of economic lifetime are always uncertain since they depend upon a number of uncontrollable external factors as well as internal factors. Based on the sensitivity analysis, we concluded that of the parameters studied in the DWDM network using existing SSMFs, the IRR is least sensitive to change in the economic lifetime under which the ICT backbone infrastructure will operate, but it is greatly affected by the changes in the capital costs and net operating profit as shown in table 6.13.

Therefore, it is apparent that errors in forecasting the economic lifetime of the DWDM network with existing SSMFs have relatively little effect on the ICT backbone infrastructure's apparent financial profit; however it will be significantly affected by the variations in capital costs or net operating profit. With a completely new build SSMFs DWDM network, the IRR is more sensitive to change in the economic lifetime under which the ICT backbone infrastructure will operate, and also is greatly affected by the changes in the capital costs and net operating profit as shown in table 6.14. Therefore the completely new build SSMFs DWDM network will be more affected by parameter variations (e.g. capital costs, net operating profit, and errors in forecasting the economic lifetime) affecting its financial performance when compared to the DWDM network using existing SSMFs. For the SONET/SDH network, the IRR is much more sensitive to any change in the parameters of the network (i.e. capital costs, net operating profit and economic lifetime) as shown in table 6.15. Therefore, any variations in these parameters will greatly affect a SONET/SDH network investment.

Parameter changes	**DWDM network (with existing SSMFs) parameters**	**Original IRR**	**New IRR after parameter changes**	**Percentage change from original IRR**
	No parameter changes	30%		
1	50 % decrease in net operating profit		10.5%	-65%
2	50 % increase in net operating profit		49%	+63%
3	50% decrease in capital cost		66%	+120%
4	50% increase in capital cost		18%	-40%
5	50% decrease in economic life		20%	-33%
6	50% increase in economic lifetime		33%	+10%

Table 6.13: Sensitivity analysis of DWDM network with existing SSMFs

Parameter changes	**DWDM network (with completely new SSMFs) parameters**	**Original IRR**	**New IRR after parameter changes**	**Percentage change from original IRR**
	No parameter changes	17%		
1	50 % decrease in net operating profit		3%	-82%
2	50 % increase in net operating profit		33%	+94%
3	50% decrease in capital cost		45%	+165%
4	50% increase in capital cost		9%	-47%
5	50% decrease in economic life		6%	-65%
6	50% increase in economic lifetime		22%	+29%

Table 6.14: Sensitivity analysis of DWDM network with completely new SSMFs

Parameter changes	SONET/SDH network parameters	Original IRR	New IRR after parameter changes	Percentage change from original IRR
	No parameter changes	7%		
1	50 % decrease in net operating profit		1%	-86%
2	50 % increase in net operating profit		24%	+243%
3	50% decrease in capital cost		35%	+400%
4	50% increase in capital cost		4%	-42%
5	50% decrease in economic life		0.4%	-94%
6	50% increase in economic lifetime		16%	128%

Table 6.15: Sensitivity analysis of SONET/SDH network

6.6. Conclusion

The objective of this research is to deploy a cost-effective and high capacity internationally connected Tanzanian ICT backbone infrastructure that will provide ICT services such as Internet, voice, videos and other multimedia interactions and be capable of providing at least 100Gb/s capacity to meet traffic demands in Tanzania at an affordable cost to the majority of the people who live in the urban and rural areas of Tanzania. In this chapter, we have verified, by using a cost analysis technique that the proposed ICT backbone infrastructure could be economical and affordable by using an optical DWDM network technology exploiting existing SSMFs in contrast to the development of the completely new build DWDM network or SONET/SDH network. Moreover, we have shown that the ICT backbone infrastructure built with existing SSMF DWDM network technology is a good investment, in terms of profitability, even if the Internet rates are reduced to half the current rates.

CHAPTER 7. CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

7.1. Conclusions

Tanzania is a developing country, which significantly lags behind the rest of the world in Information and communication technology (ICT), especially for the Internet. Internet connectivity to the rest of the world is via expensive satellite links, thus leaving the majority of the population unable to access the Internet due to the high cost.

In most places around the world the ICT backbone infrastructures are supported by optical fibre technology, most notably dense wavelength division multiplexed (DWDM) networks. Optical DWDM networks have revolutionised long distance data transport and have resulted in high capacity data highways, cost reductions, extremely low bit error rate, and operational simplification of the overall ICT backbone infrastructure.

Optical DWDM networks can provide vast amounts of information for every resident and also provide global access for schools, universities, hospitals and community centres. Innovations in ICT backbone infrastructures coupled with optical DWDM networks, have lowered the costs of providing ICT services to virtually any location, for example from an inner-city neighborhood to a rural village or to remote areas in other places of the world. DWDM network technology provides many benefits such as scalable capacity, transparency, and survivability. Internationally, DWDM networks have expanded significantly in ICT backbone infrastructure solutions and are more capable than other network technologies of delivering a high bandwidth in a flexible manner, where and when needed. ICT infrastructure development is a fundamental requirement to facilitate national economic development.

The objective of this research is to present a cost-effective Tanzanian ICT backbone infrastructure. An ICT backbone infrastructure for Tanzania using optical DWDM network technology would un-lock bandwidth bottlenecks and provides higher capacity, which will provide ICT services such as Internet, voice, videos and other multimedia interactions at an affordable cost to the majority of the people who live in the urban and rural areas of Tanzania.

The DWDM network technology concept was explored to maximise the use of the existing standard single mode fibre (SSMF) in Tanzania. Using already installed single mode fibre; a network topology for the Tanzanian ICT backbone infrastructure has been developed.

This research has demonstrated how a DWDM network is implemented using 40-wavelength channels with 2.5 Gb/s on each channel with the use of SSMFs and other necessary optical components. Using this design it is possible to deliver an ICT backbone infrastructure that can handle the required ICT services, and be capable of providing at least 100 Gb/s capacity. The low bit rate at 2.5 Gb/s per wavelength channel was chosen so as to make the DWDM network less vulnerable to system impairments such as chromatic dispersion, polarization-mode dispersion, and nonlinear effects; this has the additional benefit of reducing the DWDM network component and maintenance costs.

The ICT backbone infrastructure presented in this research yields enough capacity to cope with the increasing traffic demand in Tanzania due to the use of 40-wavelengths channels and a network management system (NMS), which prevents wavelength blocking and assigns and switches wavelengths across multiple users independently of each other. Also it is an effective solution due to the reduction in the ICT connection charge, since it will be connected to the rest of the world by means of the East African submarine cable (EASSy). This is a more cost effective solution than the existing ICT infrastructures, which connects ICT users to the rest of the world by means of Satellite links. The ICT backbone infrastructure integrates to the metro networks (e.g. SONET/SDH and IP/MPLS) and access networks (e.g. DSL and WiMAX) to provide ICT services to the majority of the people who live in both urban and rural areas.

Quantitative analysis compares the system impairments, which occur at data transmission rates of 2.5 Gb/s and 10 Gb/s per wavelength channel over a long distance (i.e. 3000 km) in a proposed optical DWDM network. The simulation results show that when an erbium-doped fibre amplifier (EDFA) incorporating a dispersion compensating fibre (DCF) is installed at each end of a SSMF (i.e. 120 km span), a data rate of 2.5 Gb/s can be successfully transmitted with an external modulator transmitter over a distance of 3000 km without any system impairments in a SSMF.

The system achieves the required BER of 10^{-12} to deliver good DWDM system performance that is sufficient to meet the quality of ICT service demand in Tanzania. In contrast, a data rate of 10 Gb/s doesn't achieve the required BER of 10^{-12} when transmitting over a distance of 3000 km due to system impairment affects; unless the span length of 120 km is reduced by half; however this solution increases the DWDM network component costs, since it will require twice the number of EDFAs (incorporating DCFs).

Finally, cost analysis techniques were used (e.g. capital costs, NPV, payback time, and IRR) to justify the economic value of incorporating the existing SSMFs installation into an optical DWDM network for the creation of a cost-effective ICT backbone infrastructure for Tanzania; this approach is compared with building the ICT backbone infrastructure using a completely new SSMF DWDM network or a SONET/SDH network.

Cost analysis results revealed that the capital cost to deploy a DWDM network with existing SSMF to meet the required ICT service demand for the majority of the people who live in urban and rural areas is USD 59.1 millions. Whilst the capital cost to deploy the DWDM network with a completely newly built SSMF and SONET/SDH is USD 120.6 millions and USD 291.9 millions respectively.

The results also revealed that when an interest rate of 10% is used for the ICT backbone infrastructure investment repayment, the NPV results for the DWDM network with existing SSMFs is positive and the payback time is approximately 4 years with an average annual cash return of 25 percent. In contrast to the completely new build SSMFs DWDM network, which shows that the NPV result is positive but the payback time is 8 years, and the average annual cash return is low at 12.6 percent. Whilst for a SONET/SDH network the NPV result is negative and the payback time is 12 years with an average annual cash return of 8%.

The cost analysis verifies that even if a high interest rate (i.e. IRR) of 30% is used for investment repayment of the ICT backbone infrastructure, the existing SSMFs DWDM network would pay back the investment costs within its economic lifetime (i.e.10-years) with an average annual cash return of 11 percent compared to a completely newly built SSMF or a SONET/SDH system. A completely newly built SSMF couldn't use more than an interest rate of 17% to pay off the investment costs within 10-years, because it would operate in debt. The same is true for the SONET/SDH Network, which couldn't exceed a 7% interest rate to pay the investment costs within 10-years. In this regard, an ICT backbone infrastructure built using existing SSMF DWDM network technology signified that it is a good investment, in terms of financial performance compared to a completely newly built SSMF or a SONET/SDH network technology.

The large ICT backbone infrastructure capacity using DWDM network technology would permit Tanzania to stop relying on satellite communication systems, permitting the country to enter the modern optical communication technology era. Therefore, rapid socio-economic development, enabled by this new ICT infrastructure, would move the country into a new age and close the digital divide with developed countries. Also it will connect Tanzania and all African countries with the rest of the world. In the long term, with most ICT services transferred to the new ICT infrastructure, the opportunities for the Tanzanian people will be huge, as will their knowledge acquisition capability. The ICT services such as Internet access, E-education, E-governance, E-banking, E-health, E-commerce, E-tourism, E-agriculture, E-manufacturing, telemedicine, etc for the majority of the people who live in urban and rural areas would improve greatly and contribute to nationwide socio-economic development. In this regard, the economy and social benefits of this ICT infrastructure model are significant and invaluable

7.2. Future Research

Albeit optical DWDM networks prove to be an attractive solution from both a technological and an economic perspective for ICT backbone infrastructures it is not a cost-effective solution at the edge of the ICT backbone as other network technologies such as SONET/SDH, IP/MPLS router, DSL or WiMAX networks are more appropriate. Therefore the ICT backbone infrastructure (DWDM network) developed in this research is used in conjunction with metro networks such as SDH/SONET and IP/MPLS router, and access networks (i.e. DSL and WiMAX networks) to provide ICT services to the majority of Tanzanian people who live in urban and rural areas. Our major research work focused on design, analysis, and comparison of the data transmission in an ICT backbone (i.e. optical DWDM network). As well as a cost analysis study for optical DWDM networks with and without existing SSMFs and SONET/SDH networks.

These metro or access networks are also required at the edge of the ICT backbone to provide end-to-end ICT services to the users. Therefore, in order to enhance this research work, it is imperative to design and analyse the data transmission on metro and access networks and produce cost analysis studies so that the quality of affordable ICT services to the end users can be assessed.

Future research should develop a traffic forecast model. Since traffic forecasting provides important guidance for development of the ICT backbone infrastructure. It is directly related to the financial performance after the ICT infrastructure has been put into operation. In this research, the traffic forecast was estimated for the total period of 10 years based on the current ICT traffic demand in Tanzania. However, to be more accurate in forecasting traffic, the traffic model should be designed to reflect the changes of dynamic traffic demand, which is changing due to the rapid development of ICT services such as mobile traffic (e.g. 3G) and Internet traffic. Hence, the ICT backbone infrastructure capacity should be increased in accordance with the dynamic growth of traffic demand.

Also a business model should be developed, since the majority of Tanzanians live in rural areas. These areas are the most backward in ICT services compared to urban areas due to the unavailability of the ICT infrastructure, which is currently caused by the high ICT service access costs. In this regard, most ICT providers were afraid to invest in these areas because it was considered a high risk business; people can't afford to pay the high costs to access ICT services. However, once the ICT infrastructure is put into operation and the current ICT usage-pricing model is replaced with a flat-rate price model, the ICT service access costs will automatically go down and the ICT service demand will grow. With this prospect, the business model should be designed to predict and show the market and growth of ICT service demand in rural areas so as to inform and attract ICT providers to rural area service provision, once the ICT backbone infrastructure is established in Tanzania.

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APPENDICES

Appendix 1: Publication list

[1] S. Pazi, C. Chatwin, R. Young, and P. Birch, An Optical WDM Network Concept for Tanzania, World Academy of Science Engineering and Technology (WASET) Proceedings of International Conference on Electronic, Circuits and System Design, vol. 54, pp.582-587, Jun 24-26, Paris, France, 2009.

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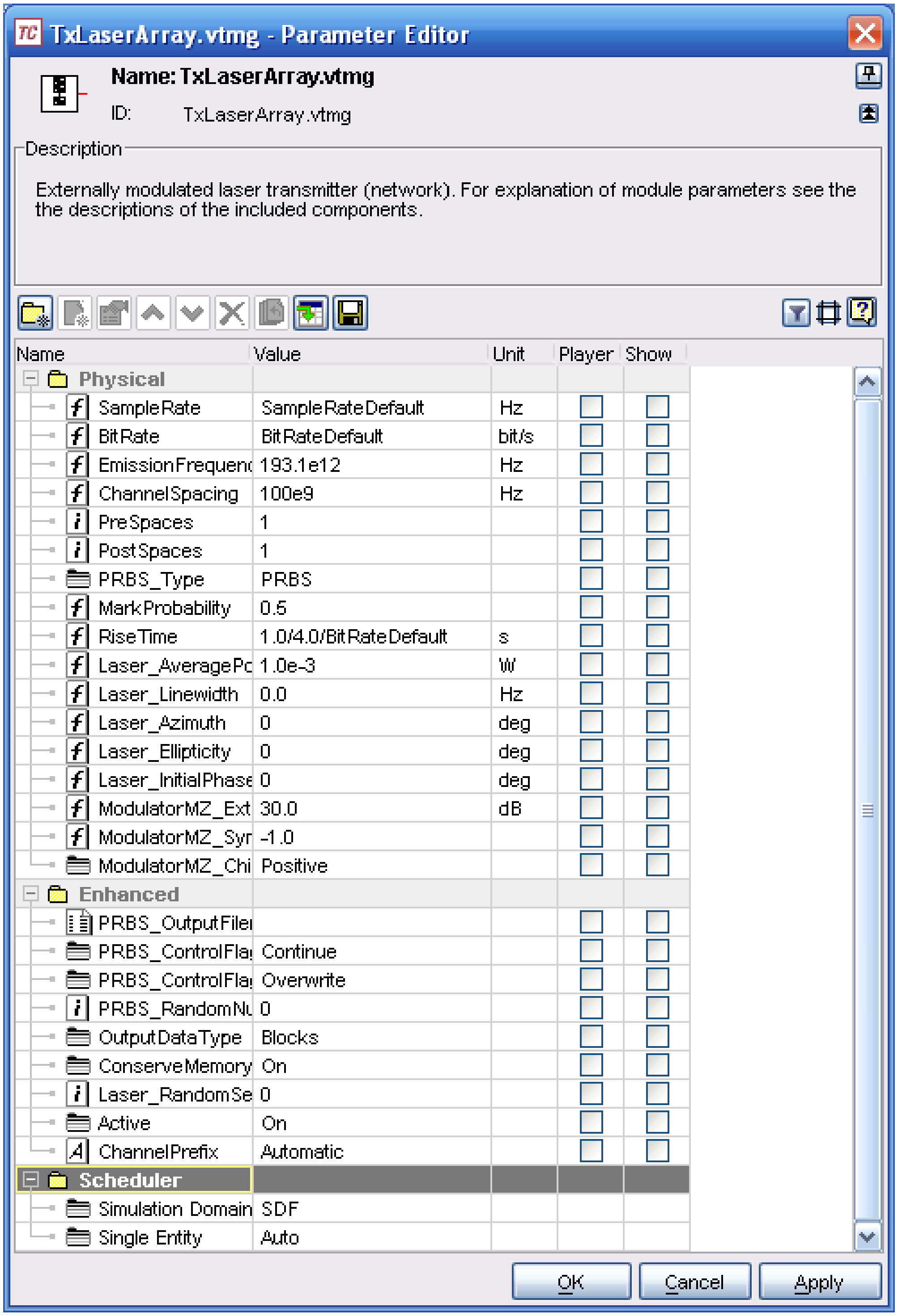
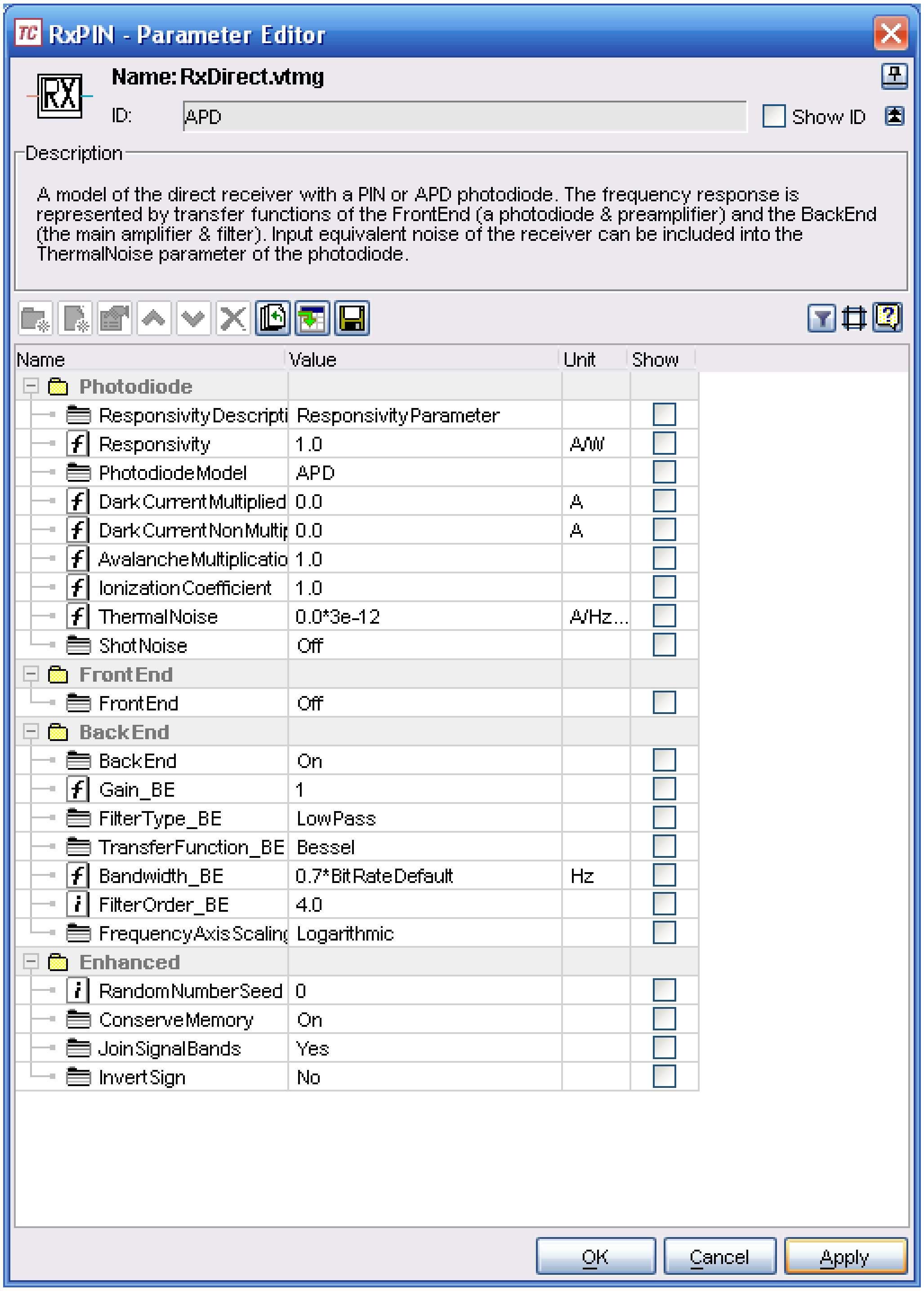
[5] S. Pazi, C. Chatwin, R. Young, P. Birch and W. Wang, Cost-effective ICT Backbone for Tanzania, European Journal of Scientific Research, vol. 39(2), pp.217-233, Jan 2010.

[6] S. Pazi, C. Chatwin, R. Young, P. Birch and W. Wang, Assessment of an Optical DWDM network as the Tanzanian ICT Backbone Infrastructure, Accepted for Publication in International Journal of African Studies, March 2010.

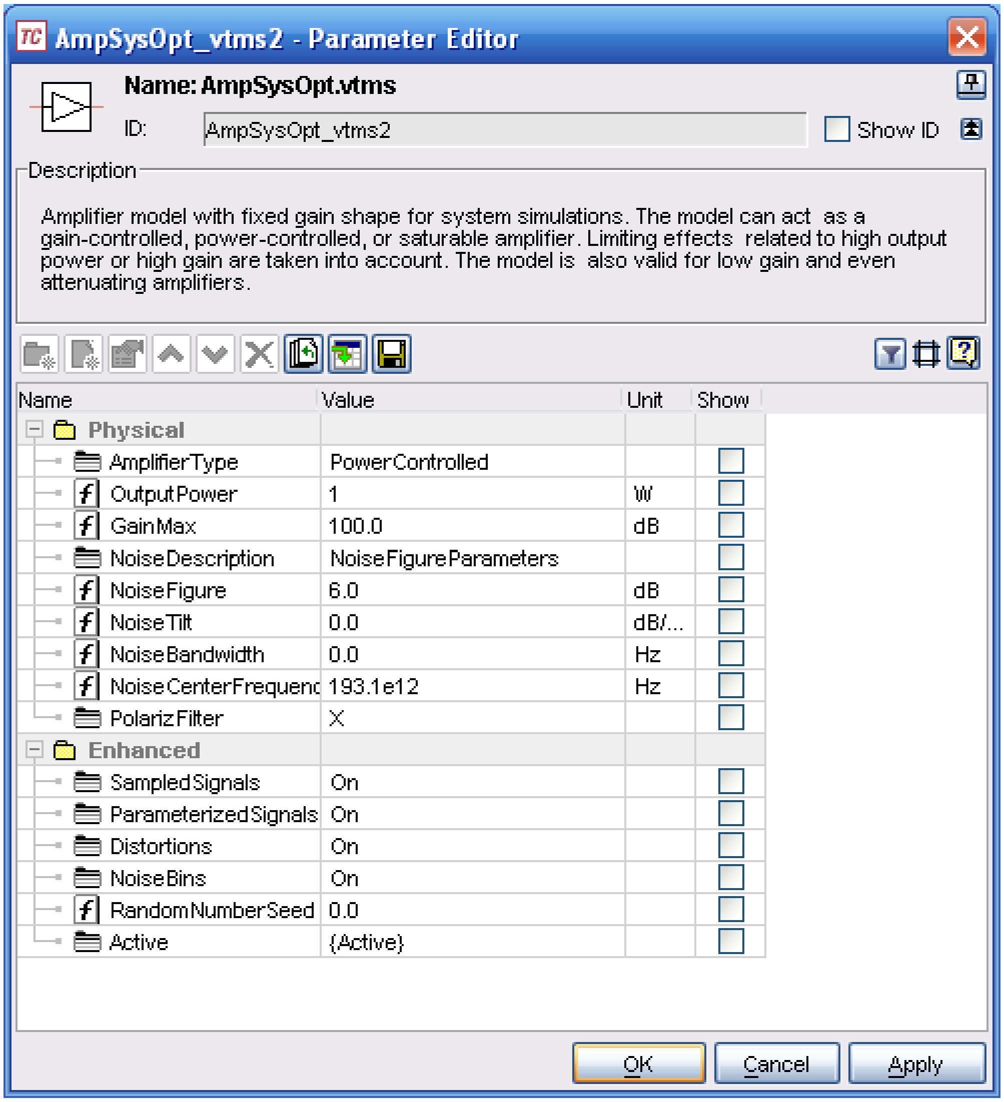
Appendix 2: VPI transmitter model details



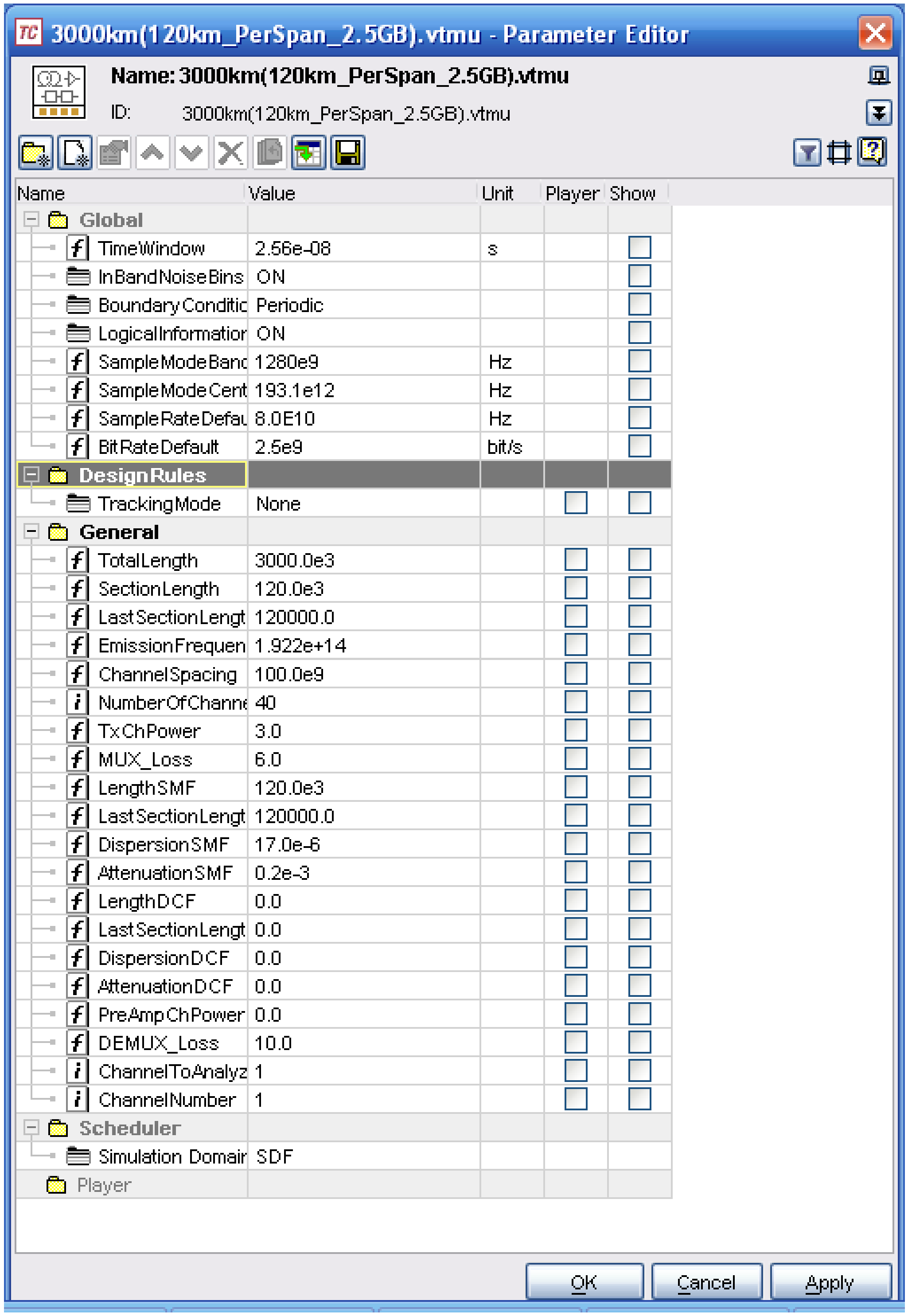
Appendix 3: VPI receiver model details



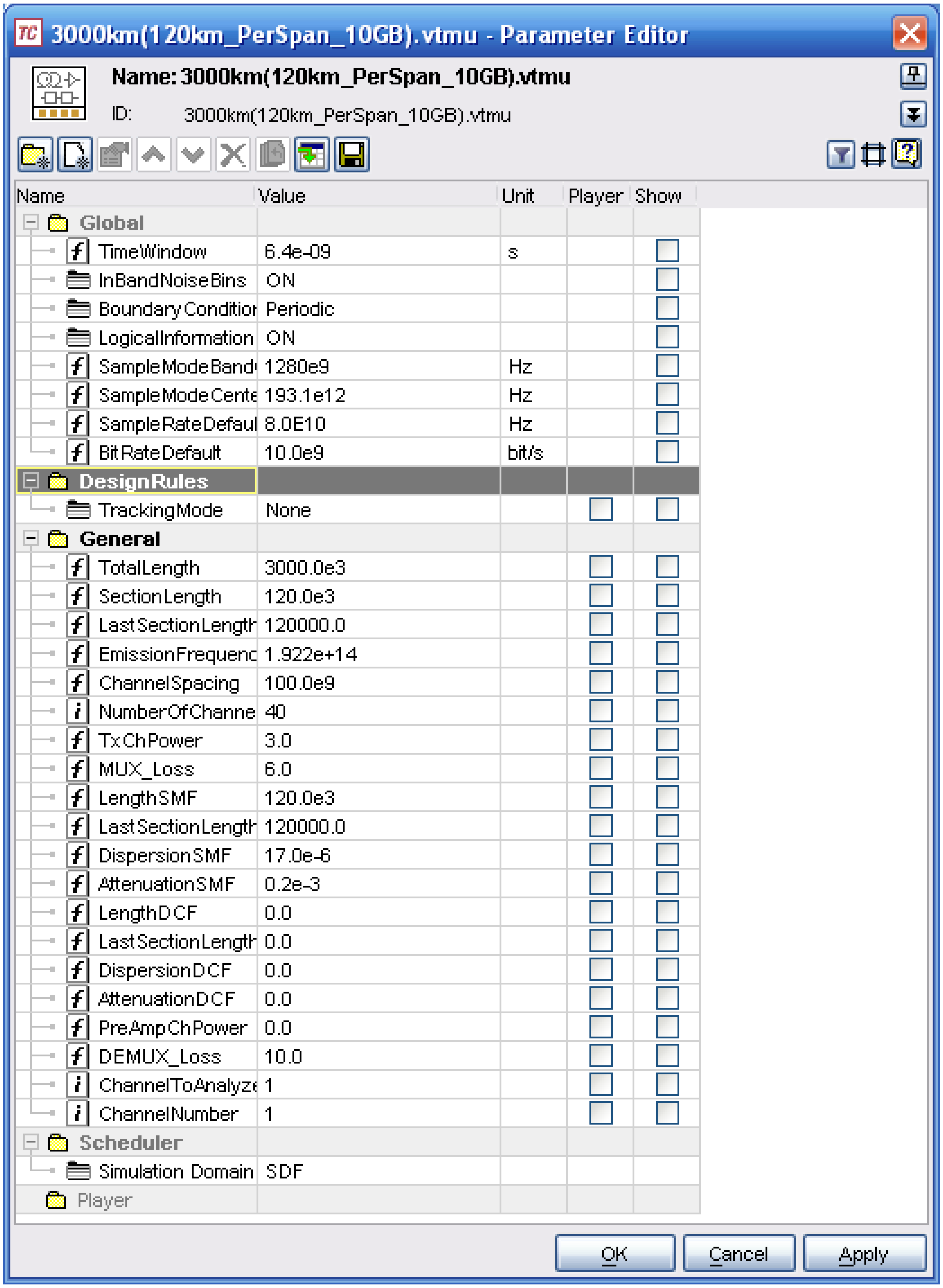
Appendix 4: VPI EDFA model details



Appendix 5: VPI Simulation model detail for 2.5 Gb/s data rates transmission



Appendix 6: VPI Simulation model details for 10 Gb/s data rates transmission


3000km(120km_PerSpan_10GB).vtmu - Parameter Editor

Name: 3000km(120km_PerSpan_10GB).vtmu

ID: 3000km(120km_PerSpan_10GB).vtmu

Name	Value	Unit	Player	Show
Global				
TimeWindow	6.4e-09	s		
InBandNoiseBins	ON			
BoundaryConditior	Periodic			
LogicalInformation	ON			
SampleModeBand	1280e9	Hz		
SampleModeCente	193.1e12	Hz		
SampleRateDefaul	8.0E10	Hz		
BitRateDefault	10.0e9	bit/s		
DesignRules				
TrackingMode	None			
General				
TotalLength	3000.0e3			
SectionLength	120.0e3			
LastSectionLength	120000.0			
EmissionFrequenc	1.922e+14			
ChannelSpacing	100.0e9			
NumberOfChanne	40			
TxChPower	3.0			
MUX_Loss	6.0			
LengthSMF	120.0e3			
LastSectionLength	120000.0			
DispersionSMF	17.0e-6			
AttenuationSMF	0.2e-3			
LengthDCF	0.0			
LastSectionLength	0.0			
DispersionDCF	0.0			
AttenuationDCF	0.0			
PreAmpChPower	0.0			
DEMUX_Loss	10.0			
ChannelToAnalyze	1			
ChannelNumber	1			
Scheduler				
Simulation Domain	SDF			
Player				

OK Cancel Apply

Appendix 7: VPI Receiver output results for 2.5 GB/s data rates

VPI ChannelAnalyzer Settings And Results File
3000km_120km_PerSpan_2_5GB__vtmu1005143923 VPI ChannelAnalyzer1

GLOBAL PARAMETERS

Continuous On
DarkCurrent 0.0
IncludeShotNoise Yes
MultipleBlockMode IndependentBlocks
Responsivity 1.0
ThermalNoise 3.0E-12
DispersionCompensation 0.0
ElecNoiseBandwidth 0.735
OpticalFilterBandwidth 4.0
SampleRange 0.0
SampleTime 0.5
SampleType Optimum
ThresholdType Optimum
Threshold 0.0010

BER parameters

IgnoreBits No
EstimationMethod Gauss
StartTimeToIgnore 0.0
NumberOfBitsToIgnore 0

CHANNEL PARAMETERS
Format: Label, Frequency, Bit Rate, LowerFilterBound, UpperFilterBound, Electrical Bandwidth, Dispersion Compensation, Sample Type, Sample Time, Sample Width, Threshold Type, Threshold, Signal Power, Noise Power, **OSNR**, Q, Qeff, BER

WDM_Channel1_el: WDM_Channel1 1.922E14 2.5E9 1.92195E14
1.92205E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174676 1.626452666694848E-5
31.837663495366495 ---- ---- ----

WDM_Channel2_el: WDM_Channel2 1.923E14 2.5E9 1.92295E14
1.92305E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174773 1.6264526666948485E-5
31.837663495366513 ---- ---- ----

WDM_Channel3_el: WDM_Channel3 1.924E14 2.5E9 1.92395E14
1.92405E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174832 1.6264526666948485E-5
31.837663495366524 ---- ---- ----

WDM_Channel4_el: WDM_Channel4 1.925E14 2.5E9 1.92495E14
1.92505E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174707 1.6264526666948485E-5
31.837663495366503 ---- ---- ----

WDM_Channel5_el: WDM_Channel5 1.926E14 2.5E9 1.92595E14
1.92605E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.0248317757981748 1.6264526666948482E-5
31.837663495366517 ---- ---- ----

WDM_Channel6_el: WDM_Channel6 1.927E14 2.5E9 1.92695E14
1.92705E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174686 1.6264526666948482E-5
31.8376634953665 ---- ---- ----

WDM_Channel7_el: WDM_Channel7 1.928E14 2.5E9 1.92795E14
1.92805E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174544 1.626452666694848E-5
31.837663495366474 ---- ---- ----

WDM_Channel8_el: WDM_Channel8 1.929E14 2.5E9 1.92895E14
1.92905E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174617 1.6264526666948485E-5
31.837663495366485 ---- ---- ----

WDM_Channel9_el: WDM_Channel9 1.93E14 2.5E9 1.92995E14
1.93005E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174742 1.6264526666948485E-5
31.837663495366506 ---- ---- ----

WDM_Channel10_el: WDM_Channel10 1.931E14 2.5E9 1.93095E14
1.93105E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174718 1.6264526666948482E-5
31.837663495366503 ---- ---- ----

WDM_Channel11_el: WDM_Channel11 1.932E14 2.5E9 1.93195E14
1.93205E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798175013 1.6264526666948482E-5
31.837663495366556 ---- ---- ----

WDM_Channel12_el: WDM_Channel12 1.933E14 2.5E9 1.93295E14
1.93305E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174825 1.6264526666948482E-5
31.837663495366524 ---- ---- ----

WDM_Channel13_el: WDM_Channel13 1.934E14 2.5E9 1.93395E14
1.93405E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174794 1.626452666694848E-5
31.837663495366517 ---- ---- ----

WDM_Channel14_el: WDM_Channel14 1.935E14 2.5E9 1.93495E14
1.93505E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174905 1.626452666694848E-5
31.837663495366538 ---- ---- ----

WDM_Channel15_el: WDM_Channel15 1.936E14 2.5E9 1.93595E14
1.93605E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174836 1.6264526666948482E-5
31.837663495366524 ---- ---- ----

WDM_Channel16_el: WDM_Channel16 1.937E14 2.5E9 1.93695E14
1.93705E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174905 1.6264526666948485E-5
31.837663495366535 ---- ---- ----

WDM_Channel17_el: WDM_Channel17 1.938E14 2.5E9 1.93795E14
1.93805E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.02483177579817493 1.6264526666948485E-5
31.83766349536654 ---- ---- ----

WDM_Channel18_el: WDM_Channel18 1.939E14 2.5E9 1.93895E14
1.93905E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174957 1.6264526666948482E-5
31.837663495366545 ---- ---- ----

WDM_Channel19_el: WDM_Channel19 1.94E14 2.5E9 1.93995E14
1.94005E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174922 1.6264526666948482E-5
31.837663495366538 ---- ---- ----

WDM_Channel20_el: WDM_Channel20 1.941E14 2.5E9 1.94095E14
1.94105E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174627 1.6264526666948475E-5
31.83766349536649 ---- ---- ----

WDM_Channel21_el: WDM_Channel21 1.942E14 2.5E9 1.94195E14
1.94205E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174634 1.6264526666948482E-5
31.83766349536649 ---- ---- ----

WDM_Channel22_el: WDM_Channel22 1.943E14 2.5E9 1.94295E14
1.94305E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174804 1.6264526666948482E-5
31.837663495366517 ---- ---- ----

WDM_Channel23_el: WDM_Channel23 1.944E14 2.5E9 1.94395E14
1.94405E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174836 1.6264526666948485E-5
31.837663495366524 ---- ---- ----

WDM_Channel24_el: WDM_Channel24 1.945E14 2.5E9 1.94495E14
1.94505E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.02483177579817482 1.6264526666948482E-5
31.83766349536652 ---- ---- ----

WDM_Channel25_el: WDM_Channel25 1.946E14 2.5E9 1.94595E14
1.94605E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.02483177579817481 1.6264526666948482E-5
31.83766349536652 ---- ---- ----

WDM_Channel26_el: WDM_Channel26 1.947E14 2.5E9 1.94695E14
1.94705E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174777 1.6264526666948482E-5
31.837663495366513 ---- ---- ----

WDM_Channel27_el: WDM_Channel27 1.948E14 2.5E9 1.94795E14
1.94805E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174718 1.626452666694848E-5
31.837663495366503 ---- ---- ----

WDM_Channel28_el: WDM_Channel28 1.949E14 2.5E9 1.94895E14
1.94905E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.02483177579817499 1.626452666694848E-5
31.837663495366552 ---- ---- ----

WDM_Channel29_el: WDM_Channel29 1.95E14 2.5E9 1.94995E14
1.95005E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798175033 1.6264526666948485E-5
31.83766349536656 ---- ---- ----

WDM_Channel30_el: WDM_Channel30 1.951E14 2.5E9 1.95095E14
1.95105E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174544 1.6264526666948482E-5
31.837663495366474 ---- ---- ----

WDM_Channel31_el: WDM_Channel31 1.952E14 2.5E9 1.95195E14
1.95205E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174957 1.626452666694848E-5
31.837663495366545 ---- ---- ----

WDM_Channel32_el: WDM_Channel32 1.953E14 2.5E9 1.95295E14
1.95305E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174763 1.6264526666948482E-5
31.83766349536651 ---- ---- ----

WDM_Channel33_el: WDM_Channel33 1.954E14 2.5E9 1.95395E14
1.95405E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174895 1.6264526666948482E-5
31.837663495366535 ---- ---- ----

WDM_Channel34_el: WDM_Channel34 1.955E14 2.5E9 1.95495E14
1.95505E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174773 1.6264526666948485E-5
31.837663495366513 ---- ---- ----

WDM_Channel35_el: WDM_Channel35 1.956E14 2.5E9 1.95595E14
1.95605E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.02483177579817479 1.626452666694849E-5
31.837663495366513 ---- ---- ----

WDM_Channel36_el: WDM_Channel36 1.957E14 2.5E9 1.95695E14
1.95705E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.0248317757981748 1.626452666694848E-5
31.83766349536652 - --- ---- ----

WDM_Channel37_el: WDM_Channel37 1.958E14 2.5E9 1.95795E14
1.95805E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.02483177579817485 1.6264526666948482E-5
31.837663495366527 ---- ---- ----

WDM_Channel38_el: WDM_Channel38 1.959E14 2.5E9 1.95895E14
1.95905E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174943 1.626452666694848E-5
31.837663495366545 ---- ---- ----

WDM_Channel39_el: WDM_Channel39 1.96E14 2.5E9 1.95995E14
1.96005E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.024831775798174707 1.626452666694848E-5
31.837663495366503 ---- ---- ----

WDM_Channel40_el: WDM_Channel40 1.961E14 2.5E9 1.96095E14
1.96105E14 1.8375E9 0.0 Optimum 0.5 0.0 Optimum
0.0010 0.02483177579817475 1.6264526666948485E-5
31.83766349536651 ---- ---- ----

Appendix 8: VPI Receiver output results for 10 Gb/s data rates

VPI ChannelAnalyzer Settings And Results File
3000km_120km_PerSpan_10GB__vtmu1005151010 VPI ChannelAnalyzer1

GLOBAL PARAMETERS

Continuous On
DarkCurrent 0.0
IncludeShotNoise Yes
MultipleBlockMode IndependentBlocks
Responsivity 1.0
ThermalNoise 3.0E-12
DispersionCompensation 0.0
ElecNoiseBandwidth 0.735
OpticalFilterBandwidth 4.0
SampleRange 0.0
SampleTime 0.5
SampleType Optimum
ThresholdType Optimum
Threshold 0.0010

BER parameters

IgnoreBits No
EstimationMethod Gauss
StartTimeToIgnore 0.0
NumberOfBitsToIgnore 0

CHANNEL PARAMETERS
Format: Label, Frequency, Bit Rate, LowerFilterBound, UpperFilterBound, Electrical Bandwidth, Dispersion Compensation, Sample Type, Sample Time, Sample Width, Threshold Type, Threshold, Signal Power, Noise Power, **OSNR**, Q, Qeff, BER

WDM_Channel1_el: WDM_Channel1 1.922E14 1.0E10 1.9218E14
1.9222E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782052462457978 0.0027724440913754465
8.071190902094658 --- ---- ----

WDM_Channel2_el: WDM_Channel2 1.923E14 1.0E10 1.9228E14
1.9232E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782058638934322 0.002772444091375446
8.071192410587075 ---- ---- ----

WDM_Channel3_el: WDM_Channel3 1.924E14 1.0E10 1.9238E14
1.9242E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782052547102276 0.002772444091375446
8.0711909227675 ---- ---- ----

WDM_Channel4_el: WDM_Channel4 1.925E14 1.0E10 1.9248E14
1.9252E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.01778207009703 0.002772444091375446
8.071195209017912 ---- ---- ----

WDM_Channel5_el: WDM_Channel5 1.926E14 1.0E10 1.9258E14
1.9262E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782068143544674 0.0027724440913754465
8.071194731914884 ---- ---- ----

WDM_Channel6_el: WDM_Channel6 1.927E14 1.0E10 1.9268E14
1.9272E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782064277119244 0.0027724440913754465
8.071193787611108 ---- ---- ----

WDM_Channel7_el: WDM_Channel7 1.928E14 1.0E10 1.9278E14
1.9282E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782069233940587 0.002772444091375445
8.071194998224133 ---- ---- ----

WDM_Channel8_el: WDM_Channel8 1.929E14 1.0E10 1.9288E14
1.9292E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782074805333302 0.0027724440913754456
8.071196358934577 ---- ---- ----

WDM_Channel9_el: WDM_Channel9 1.93E14 1.0E10 1.9298E14
1.9302E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782053432264834 0.002772444091375447
8.071191138952441 - --- ---- ----

WDM_Channel10_el: WDM_Channel10 1.931E14 1.0E10 1.9308E14
1.9312E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782070380620688 0.002772444091375446
8.07119527827974 ---- ---- ----

WDM_Channel11_el: WDM_Channel11 1.932E14 1.0E10 1.9318E14
1.9322E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.0177820734368731 0.0027724440913754465
8.071196024713318 ---- ---- ----

WDM_Channel12_el: WDM_Channel12 1.933E14 1.0E10 1.9328E14
1.9332E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.01778206900299933 0.0027724440913754465
8.071194941820956 ---- ---- ----
WDM_Channel13_el: WDM_Channel13 1.934E14 1.0E10 1.9338E14
1.9342E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782058109225066 0.002772444091375446
8.07119228121521 ---- ---- ----

WDM_Channel14_el: WDM_Channel14 1.935E14 1.0E10 1.9348E14
1.9352E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782079339615717 0.0027724440913754465
8.071197466349544 ---- ---- ----

WDM_Channel15_el: WDM_Channel15 1.936E14 1.0E10 1.9358E14
1.9362E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.01778205214209611 0.002772444091375446
8.071190823852064 ---- ---- ----

WDM_Channel16_el: WDM_Channel16 1.937E14 1.0E10 1.9368E14
1.9372E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782074850889767 0.0027724440913754465
8.071196370060903 ---- ---- ----

WDM_Channel17_el: WDM_Channel17 1.938E14 1.0E10 1.9378E14
1.9382E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782068337143277 0.0027724440913754456
8.071194779197803 ---- ---- ----

WDM_Channel18_el: WDM_Channel18 1.939E14 1.0E10 1.9388E14
1.9392E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.01778206362551673 0.002772444091375447
8.071193628469077 ---- ---- ----

WDM_Channel19_el: WDM_Channel19 1.94E14 1.0E10 1.9398E14
1.9402E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782058668835005 0.0027724440913754465
8.071192417889772 ---- ---- ----
WDM_Channel20_el: WDM_Channel20 1.941E14 1.0E10 1.9408E14
1.9412E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782057019521555 0.002772444091375447
8.071192015074903 ---- ---- ----

WDM_Channel21_el: WDM_Channel21 1.942E14 1.0E10 1.9418E14
1.9422E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782058139477846 0.0027724440913754465

8.071192288603902 ---- ---- ----

WDM_Channel22_el: WDM_Channel22 1.943E14 1.0E10 1.9428E14
1.9432E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.01778208385956747 0.0027724440913754465
8.07119857026423 ---- ---- ----

WDM_Channel23_el: WDM_Channel23 1.944E14 1.0E10 1.9438E14
1.9442E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782058691362027 0.002772444091375446
8.07119242339159 ---- ---- ----

WDM_Channel24_el: WDM_Channel24 1.945E14 1.0E10 1.9448E14
1.9452E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.0177820632068693 0.0027724440913754465
8.071193526222075 ---- ---- ----
WDM_Channel25_el: WDM_Channel25 1.946E14 1.0E10 1.9458E14
1.9462E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782056771063516 0.0027724440913754456
8.071191954393536 ---- ---- ----

WDM_Channel26_el: WDM_Channel26 1.947E14 1.0E10 1.9468E14
1.9472E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.01778205213359787 0.002772444091375445
8.071190821776524 ---- ---- ----

WDM_Channel27_el: WDM_Channel27 1.948E14 1.0E10 1.9478E14
1.9482E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782068862514138 0.0027724440913754456
8.071194907510021 ---- ---- ----

WDM_Channel28_el: WDM_Channel28 1.949E14 1.0E10 1.9488E14
1.9492E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782053987351453 0.0027724440913754465
8.071191274522304 ---- ---- ----

WDM_Channel29_el: WDM_Channel29 1.95E14 1.0E10 1.9498E14
1.9502E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782069052813137 0.0027724440913754456
8.071194953987067 ---- ---- ----

WDM_Channel30_el: WDM_Channel30 1.951E14 1.0E10 1.9508E14
1.9512E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782057615027602 0.002772444091375445
8.071192160516452 ---- ---- ----

WDM_Channel31_el: WDM_Channel31 1.952E14 1.0E10 1.9518E14
1.9522E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782063709326383 0.002772444091375446
8.071193648938058 ---- ---- ----

WDM_Channel32_el: WDM_Channel32 1.953E14 1.0E10 1.9528E14
1.9532E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782046714635177 0.0027724440913754456
8.071189498292632 ---- ---- ----

WDM_Channel33_el: WDM_Channel33 1.954E14 1.0E10 1.9538E14
1.9542E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782062166849993 0.002772444091375446
8.071193272216309 ---- ---- ----

WDM_Channel34_el: WDM_Channel34 1.955E14 1.0E10 1.9548E14
1.9552E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.0177820634966897 0.002772444091375446
8.071193597005426 ---- ---- ----

WDM_Channel35_el: WDM_Channel35 1.956E14 1.0E10 1.9558E14
1.9562E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782054169652988 0.0027724440913754473
8.071191319046152 ---- ---- ----

WDM_Channel36_el: WDM_Channel36 1.957E14 1.0E10 1.9568E14
1.9572E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.01778206720711445 0.002772444091375446
8.071194503208929 ---- ---- ----

WDM_Channel37_el: WDM_Channel37 1.958E14 1.0E10 1.9578E14
1.9582E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782063800116394 0.0027724440913754456
8.071193671111864 ---- ---- ----

WDM_Channel38_el: WDM_Channel38 1.959E14 1.0E10 1.9588E14
1.9592E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.0177820470543408 0.0027724440913754465
8.071189581259615 ---- ---- ----

WDM_Channel39_el: WDM_Channel39 1.96E14 1.0E10 1.9598E14
1.9602E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010
0.017782074361336886 0.002772444091375446
8.071196250496612 ---- ---- ----

WDM_Channel40_el: WDM_Channel40 1.961E14 1.0E10 1.9608E14 1.9612E14 7.35E9 0.0 Optimum 0.5 0.0 Optimum 0.0010 0.017782074434815862 0.002772444091375446 **8.071196268442502** ---- ---- ----