CAPACITY FORECASTING AND DESIGN OF AN OPTICAL FIBER BACKBONE NETWORK IN BANGLADESH

by

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IN
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A thesis submitted to the Department of Electrical and Electronic Engineering of
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DECLARATION

I, do hereby, declare that neither this dissertation nor any part of it has been submitted elsewhere for the award of any degree or diploma.

Signature of the candidate
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DEDICATION

To my parents, my wife and my son

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ABSTRACT

Bangladesh has joined the submarine cable consortium in the 4th September 2002. However, the deployment of submarine cable connectivity alone would not ensure provisions for different e-services, such as data, voice, video, health care etc. throughout the country. Proper analysis of demand, planning of backbone/access networks, resource allocation and bandwidth utilization are necessary in this regard to harness the benefit of the connectivity. The present work performs, for the first time, a comprehensive study on the existing capacity of the deployed submarine cable connectivity and its present scenario in terms of its use in Bangladesh. A demand forecasting model has been developed for the telecommunications bandwidth requirement relating the four major user classes, such as, voice, internet, mobile operators and other new applications.

Following the development of the bandwidth forecasting model, an extensive study has been carried out to survey the existing network facilities, its access networks, redundancy schemes and QoS issues etc. of BTCL. The major lapses of the existing network have also been identified, especially, at the levels of resource allocation and redundancy measures adopted. After a careful study and proper analysis, an optimum network plan has been proposed for the major inter-city routes of the optical fiber backbone network. The proposed network plan includes the deployment of redundant routes or paths for ensuring a reliable digital communication.

The Quality of Service (QoS) parameters, such as BER, Q-factor, Noise Figure etc. are then simulated. Part of the backbone network, connecting Dhaka to Cox's Bazar landing station, is then simulated using the OptSim simulator for the existing BTCL link, and two other link designs as proposed in the current research. The hardware complexity and the QoS parameters are then compared between the designed links and the existing link of BTCL at hand.

The findings of the reserch would help the planners and decision makers to design and better utilize the full potential of the submarine cable connectivity in Bangladesh. Some very basic technical and socio-economic problems of submarine cable connectivity, and the challenges of utilizing its full potential are also identified here.

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LIST OF SYMBOLS

$\Delta\tau$	Differential group delay
n_s	Effective refractive index along the slow axis
n_f	Effective refractive index along the fast axis
f_{IF}	Intermediate frequency
$P(1/0)$	The probability of deciding 1 when 0 is received
$P(0/1)$	Probability of deciding 0 when 1 is received
σ_0^2	Noise variance for bit 0
σ_1^2	Noise variance for bit 1
T_0	Full width half maximum of the bit
T	Bit interval or bit period
i_m	Total output photo-detector current
ϕ_n	Phase noise of the transmitting laser
λ	Wavelength
R_b	Bit rate
$p(t)$	The elementary pulse shape
R_d	Responsivity of the photodetector
σ_m^2	Total noise power
f_c	Carrier frequency
P_T	The transmitted optical power
Δf	The peak frequency deviation
D	Chromatic dispersion L
L	Fiber length
$i_n(t)$	Total noise current
P_s	Output power at the fiber end
P_{Lo}	The local oscillator power
η	Phase distortion of the signal
ρ	Intermediate frequency SNR
σ_k	Generic encoder state
ε	Small power penalty
λ_1	Pump wavelength
λ_2	Low-power probe continuous wave
P_0	The pump power
n_{eff}	Effective refractive index
$\Delta\lambda$	Grating bandwidth
$B(\omega)$	Fiber birefringence

LIST OF ABBREVIATIONS AND ACRONYMS

ADSL	Asymmetrical Digital Subscriber Line
AEL	Allowable Exposure Limit
APD	Avalanche Photodiode
AR	Autoregressive
ASE	Amplified Spontaneous Emission
ASK	Amplitude Shift Keying
ATM	Asynchronous Transfer Mode
BER	Bit Error Rate
BTCL	Bangladesh Telecom Company Limited
CD	Chromatic Dispersion
DCF	Dispersion Compensator Fiber
DEMUX	De-multiplexer
DGD	Differential Group Delay
DPG	Digital Pair Gain
DPSK	Differential Phase Shift Keying
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
FSK	Frequency Shift Keying
FTTB	Fiber-to-the-building
FTTC	Fiber-to-the-curb
FTTH	Fiber-to-the-house
GVD	Group Velocity Dispersion
HDSL	High-bit-rate Digital Subscriber Line
ICT	Information and Communication Technology
IEC	International Electro-technical Commission
IF	Intermediate Frequency
ILDTS	International Long Distance Telecom Services
IM-DD	Intensity Modulation – Direct Detection
IPLC	International Private Leased Circuit

ISI	Inter-symbol interference
ISP	Internet Service Provider
ITU	International Telecommunication Union
LAN	Local Area Network
LASER	Light Amplification by Stimulating Emission of Radiation
LED	Light Emitting Diode
LMS	Least Mean Square
MMF	Multimode Fiber
MPLS	Multi-protocol Label Switching
MRC	Monthly Rental Charge
MSAN	Multi Service Access Network
MUX	Multiplexer
MZI	Mach-Zehnder Interferometer
NRZ	Non-return to Zero
OADM	Optical Add-drop Multiplexers
ONU	Optical Network Unit
OOK	On-Off Keying
OSP	Online Service Provider
OXC	Optical Cross-connect
PDA	Personal Digital Assistant
PIN	Positive Intrinsic Negative
PMD	Polarization Mode Dispersion
PoP	Point of Presence
POTS	Plain Old Telephone Service
RF	Radio Frequency
RZ	Return to Zero
SBS	Stimulated Brillouin Scattering
SDH	Synchronous Digital Hierarchy
SMF	Single Mode Fiber
SMW 4	SEA-ME-WE-4
SNR	Signal-to-Noise Ratio

SOA	Semiconductor Optical Amplifier
SPM	Self Phase Modulation
VPN	Virtual Private Network
WDM	Wavelength Division Multiplexing
Wi-MAX	Worldwide Interoperability for Microwave Access
WWW	World Wide Web
ZMD	Zero Material Dispersion

CHAPTER 1

INTRODUCTION

Fiber optic communication developed very quickly after the first low-loss fibers produced in 1970. Operational fiber systems are now common, and new installations and applications will continue to appear for many years. Growth of the Internet, e-mail, video and television in all the continents has led to an immense growth of optical submarine cable network and new projects around the world. Due to the tremendous growth of the Internet and World Wide Web (WWW), the data rate of the current optical systems has been pushed to 10 Gbit/s~ 40 Gbit/s and beyond. However, an extensive study is, therefore, needed to survey the potential use of the submarine cable bandwidth, to evaluate the requirements of different users, assess the limitations of the existing network, simulate the Quality of Service (QoS) parameters like Q-factor, BER, and Noise Figure (NF) [1– 6], and investigate if a better alternative network plan be designed. In this chapter, at first we give an historical perspective of optical communication, then we provide some key concepts of optical transmission system and its quality of service parameters i.e. performance measurement, literature review, motivation of the research work and its objectives, and finally an overview of this dissertation.

1. 1 Background

Most of the sea-side countries of the world are now using submarine cable, which are comparatively cheaper, higher bandwidth, more reliable and provide more secure communication facility than the traditional satellite system. We are very fortunate that Bangladesh has officially signed an agreement to join South East Asia – Middle East – Western Europe 4 (SEA-ME-WE 4) Submarine Cable Consortium on the 4th of September 2002 [7]. Later, the Submarine Cable System has officially been launched in Bangladesh on May 21, 2006 [8, 9].

As a result of joining this consortium, Bangladesh now be able to achieve high speed and comparatively low cost communication than the previous satellite system. Before the existence of SEA-ME-WE 4 (SMW 4), Internet Service Providers (ISPs) have been using VSAT which is very expensive, offers limited bandwidth and suffers from lower speed.

OS-W or OSW-100G type of cables are used in submarine cables and its' major and design parameters are given in Table 1.1 and Table 1.2.

Table 1.1: Parameters of OS-W or OSW-100G type Submarine cables

No.	Item	Parameter	
		OS-W	OSW-100G
1	Line Bit Rate	10-20 Gbps	160 Gpbs
2	Line Code	Binary, NRZ	Binary, RZ
3	Bit Rate/ Channel	Nominal 2.5 Gbps	Nominal 10 Gbps
4	Number of Channels	Up to 8	Up to 16
5	Number of Fiber Pair	Up to 4	Up to 4
6	Optical Wavelength	1550nm-1560nm	1545nm-1555nm
7	Max. System Length	6,000 km	9,000 km
8	Maximum Sea Depth	8,000 km	8,000 km
9	Repeater Supervisory	Span Gain monitoring	Command and response
10	Design Life	Longer than 25 years	Longer than 25 years
11	Reliability	Less than 3 ship repairs	Less than 3 ship repairs

Table 1.2: Major design parameters of OS-W or OSW-100G type Submarine cables

No.	Item	Parameter
1	Optical Loss	0.21 dB/km
2	Mode field Diameter	Not less than 8.6 μm
3	Polarization Mode Dispersion	Not more than 0.25 ps/$\sqrt{}$km
4	Chromatic Dispersion	-2 ps/nm-km at 1558.5 nm
5	Chromatic Dispersion Slope	0.1 ps/km-nm^2

Wave Division Multiplexing (WDM) technique is used in the transmission of signals through the Optical Fibers of Submarine Cable. Each Fiber pair can carry 64 wavelengths and each wave length is capable of transmitting 10 Gbps. For SMW 4 system, at present the trunk line will be equipped with 10 x a i.e 10 x 10 Gbps and the omnibus line will be equipped with 6 x a i.e 6 x 10 Gbps, where, a is the bit rate of the system. But each pair of Fiber is capable of carrying 64 x a i.e 64 x 10 Gbps. Therefore the ultimate final capacity of the two fiber pair would be 2 x 64 x 10 Gbps i.e 1.28 Tbps. The life time of the submarine cable is expected to be 25 years [8].

1.2 Objectives

The Government of Bangladesh has declared the Information and Communication Technology (ICT) as a thrust sector, and BTCL (formerly BTTB) has been assigned the huge responsibility for building (i) ICT infrastructure throughout the country to ensure access to information for every citizen, (ii) to provide service at an affordable cost, and (iii) to establish direct connectivity with the international communication backbone through the submarine cable network [10 – 12].

The main objectives of the current research are as follows:

(a) To develop a forecasting formula for predicting the future demand (in terms of bandwidth) of various users and telecom service providers in Bangladesh.
(b) To study the existing backbone network facilities of BTCL and design an appropriate network plan for the major intercity backbone networks to meet the demand as predicted by the forecasting formula.
(c) Finally, to simulate the QoS parameters of the designed backbone network and compare its performance with the performance of the existing BTCL network using an appropriate simulator.

1.3 Methodologies

Firstly, proper documentation has been collected from the respective organizations to study the present and future capacity of the submarine cable, which helped to assess the potential use of the available bandwidth. For predicting the future demand of telecommunications bandwidth in Bangladesh, at first statistics and data on past, present and anticipated future bandwidth demand have been collected from the Internet Service Providers (ISPs), land-phone, mobile and IPLC operators, and also from other new service providers (Call centres, VoIP operators etc.). Then, by making a comprehensive study on each operator’s past and present growth, relative factors has been assigned for bandwidth demand of each application, and finally a forecasting equation has been formulated. This model has then been used for utilization of bandwidth projection up to 2011 and beyond. This has been compared with the available SMW-4 submarine cable capacity to assess whether or not the demand could be met by proper utilization of the available bandwidth.

Following the development of the bandwidth forecasting formula, an extensive study has been carried out to survey the existing network facilities, its access networks, redundancy schemes and QoS issues etc. of BTCL and other private operators. The problems that are currently being faced by them are collected using proper feedback forms. After a careful study and close scrutiny, it was possible to determine whether or not the existing facilities and infrastructures are at par with the growing demand as forecast proposed by the realistic model. The major lapses of the existing network were identified, especially, at the levels of resource allocation and redundancy measures adopted. After a careful study and proper analysis, an optimum backbone network plan has been proposed for the following major inter-city routes of Bangladesh.

(i) Dhaka – Comilla – Feni - Chittagong – Chiringa - Cox’sBazar;
(ii) Comilla – Chandpur – Noakhali – Feni;
(iii) Dhaka – Gazipur - Mymensingh – Netrokona – Sunamgonj – Sylhet;
(iv) Mymensingh – Sherpur – Rangpur;
(v) Dhaka - Tangail – Sirajgonj – Bogra – Rangpur;
(vi) Rangpur - Rajshahi – Pabna – Khustia – Jessore – Khulna - Mongla - Barishal;
(vii) Faridpur – Khustia;
(viii) Dhaka – Narshidi - Brahmonbaria – Habigonj – Moulovibazar – Sylhet and
(ix) Dhaka – Manikgonj – Faridpur – Gopalgonj – Barishal.

The proposed network plan includes the deployment of redundant routes or paths where necessary. A centralized monitoring system has also been proposed in Dhaka, which would conduct route management for proper utilization of the submarine cable bandwidth. It would also ensure proper protection against any unforeseeable outages.

From the proposed network plan, the Quality of Service (QoS) parameters, such as BER, Q-factor and Noise Figure has been formulated. The segments of the backbone network, connecting the major cities of the country, are then simulated using the OptSim simulator. Finally, a comparative study has been carried out between the proposed network and the existing network of BTCL at hand (BTCL has a projected plan up to 2011) in terms of hardware complexity and the QoS parameters.

The results of the study may be used as a guideline for the network designers for planning, installation and expansion of the national high speed backbone network for better utilization of the submarine cable connectivity in Bangladesh. The findings will also help in designing a suitable network plan for ensuring a cost-effective, high speed and fault tolerant Internet communication.

1.4 Organization of this Dissertation

The dissertation has been organized as follows:

The background, objectives and methodologies of the current research have been described in the current chapter, which is named as Chapter 1.

Chapter 2 describes a brief comparison between the optical fiber and electrical transmission systems. Several other aspects like, the governing standard, transmission windows, optical communication system, fiber-optic-link design, requirements in the link design are then described. Different losses of optical fibers and its characteristic are also discussed. A data sheet of different types of optical fiber are provided and then the overall dispersion equation is derived. The effects of dispersion on bandwidth of optical fibers are also discussed. This chapter also goes on to describe the optical transmission system.

Chapter 3 describes capacity forecasting of the existing backbone network in Bangladesh. By making a comprehensive study on each operator’s past and present growth, relative factors are assigned for bandwidth demand of each application, and finally a forecasting equation is formulated. This model is then used for utilization of bandwidth projection up to 2011 and beyond, and is compared with the available SMW-4 submarine cable capacity.

Chapter 4 describes the design plan of the optical fiber backbone network in Bangladesh, and the recommended redundancy schemes for both national and international backbone networks with proper topologies.

Chapter 5 describes the results and discussion of different optical backbone networks followed by simulation analysis using the OptSim simulator, and the BER, Q-factor and Noise Figure performance results are evaluated. Finally, the optimum results are considered for the choice of an appropriate design.

Chapter 6 focuses on conclusions of the thesis, summarizes the achievements of the research and provides recommendations for future work.

A list of references is included at the end of this dissertation.

CHAPTER 2

OPTICAL COMMUNICATION SYSTEM AND ITS TRANSMISSION CHARACTERISTICS

In this chapter, a brief comparison is provided between the optical fiber and electrical transmission systems. Several other aspects like, the governing standard, transmission windows, optical communication system, fiber-optic-link design, requirements in the link design are then described. Different losses of optical fibers and its characteristic are also discussed. A data sheet of different types of optical fiber are provided and then the overall dispersion equation is derived. Then the effects of dispersion on bandwidth of optical fibers are also discussed. The optical transmission system is also described and finally, a comparison between multi-channel multi-fiber and multi-channel single-fiber optical transmission system is provided.

2.1 Comparison of Optical Transmission with Electrical Transmission

The choice between optical fiber and electrical (or copper) transmission for a particular system is made based on a number of trade-offs. Optical fiber is generally chosen for systems requiring higher bandwidth or spanning longer distances than electrical cabling can accommodate. The main benefits of fiber are its exceptionally low loss, allowing long distances between amplifiers or repeaters; and its inherently high data-carrying capacity, such that thousands of electrical links would be required to replace a single high bandwidth fiber. Another benefit of fiber is that even when run alongside each other for long distances, fiber cables experience effectively no crosstalk, in contrast to some types of electrical transmission lines.

In short distance and relatively low bandwidth applications, electrical transmission is often preferred because of its

- Lower material cost, where large quantities are not required.
- Lower cost of transmitters and receivers.
- Ease of splicing.
- Capability to carry electrical power as well as signals.

Because of these benefits of electrical transmission, optical communication is not common in short box-to-box, backplane, or chip-to-chip applications; however, optical systems on those scales have been demonstrated in the laboratory.

In certain situations fiber may be used even for short distance or low bandwidth applications, due to other important features:

- Immunity to electromagnetic interference, including nuclear electromagnetic pulses (although fiber can be damaged by alpha and beta radiation).
- High electrical resistance, making it safe to use near high-voltage equipment or between areas with different earth potentials.
- Lighter weight, important, for example, in aircraft.
- No sparks, important in flammable or explosive gas environments.
- Not electromagnetically radiating, and difficult to tap without disrupting the signal, important in high-security environments.
- Much smaller cable size — important where pathway is limited, such as networking an existing building, where smaller channels can be drilled.

2.2 Governing standards

In order for various manufacturers to be able to develop components that function compatibly in fiber optic communication systems, a number of standards have been developed. The International Telecommunications Union publishes several standards related to the characteristics and performance of fibers themselves, including

- ITU-T G.651, Characteristics of a 50/125 µm multimode graded index optical fiber cable
- ITU-T G.652, Characteristics of a single-mode optical fiber cable

Other standards, produced by a variety of standards organizations, specify performance criteria for fiber, transmitters, and receivers to be used together in conforming systems. Some of these standards are the following:

- 10 gigabit Ethernet
- FDDI
- Fiber Channel
- Gigabit Ethernet
- HIPPI
- Synchronous Digital Hierarchy
- Synchronous Optical Networking

TOSLINK is the most common format for digital audio cable using plastic optical fiber to connect digital sources to digital receivers.

2.3 Transmission windows

Each of the effects that contributes to attenuation and dispersion depends on the optical wavelength, however wavelength bands exist where these effects are weakest, making these bands, or windows, most favorable for transmission. These windows have been standardized, and the current bands defined are the following Table 2.1 [13].

Table 2.1 : Wavelength range of different bands

Band	Description	Wavelength Range
O band	Original	1260 to 1360 nm
E band	Extended	1360 to 1460 nm
S band	short wavelengths	1460 to 1530 nm
C band	conventional ("erbium window")	1530 to 1565 nm
L band	long wavelengths	1565 to 1625 nm
U band	ultralong wavelengths	1625 to 1675 nm

Note that this table shows that current technology has managed to bridge the second and third windows- originally the windows were disjoint.

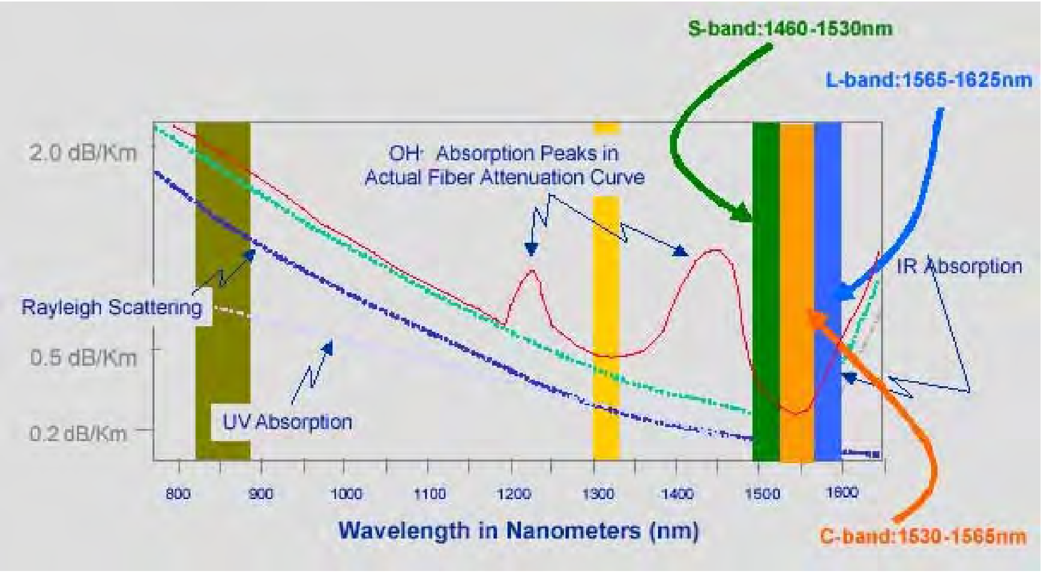


Fig. 2.1: Fiber Attenuation Characteristic

Historically, the first window used was from 800-900 nm; however losses are high in this region and because of that, this is mostly used for short-distance communications. The second window is around 1300 nm, and has much lower losses. The region has zero dispersion. The third window is around 1500nm, and is the most widely used (Fig. 2.1). This region has the lowest attenuation losses and hence it achieves the longest range. However it has some dispersion, and dispersion compensators are used to remove this. The historical perspective of the optical fiber communication systems has been included in Appendix-A.

2.4 Fiber Optic Link Design

To establish the communication through optical fiber one must fellow appropriate procedures to design a usable optical fiber link to meet some desired specifications, such as, a certain minimum coupling loss, low bit error rate, some specific data rate, etc. The procedure is iterative, that is at first certain assumptions are made, and the design is then carried out based on those assumptions. The design is not finished at that point; however, the designer must verify that it meets the objectives and represents economical and technical solutions. If not, it is required to pass another combination through the design procedure. In particular, the assumptions need to be inspected to determine if changes might provide a simpler or cheaper alternative.

The starting point for optical fiber communication link design is choosing the operating wavelength, the type of source (i.e. LED or LASER), and whether a single mode or multimode fiber is required. In a link design, one usually knows (or estimates) the data rate required to meet the objectives. From this data rate and an estimate of link length, one chooses the wavelength, the type of source, and the fiber type. Also, the requirements for the link design must be chosen in such a way that the losses (e.g. source to fiber coupling loss, fiber to fiber coupling loss, fiber to detector coupling loss, dispersion, attenuation etc.) involved in those requirements should be maintained to a minimum. The optical-fiber-link design simulator flow chart is given below in Fig. 2.2 [14 - 15].

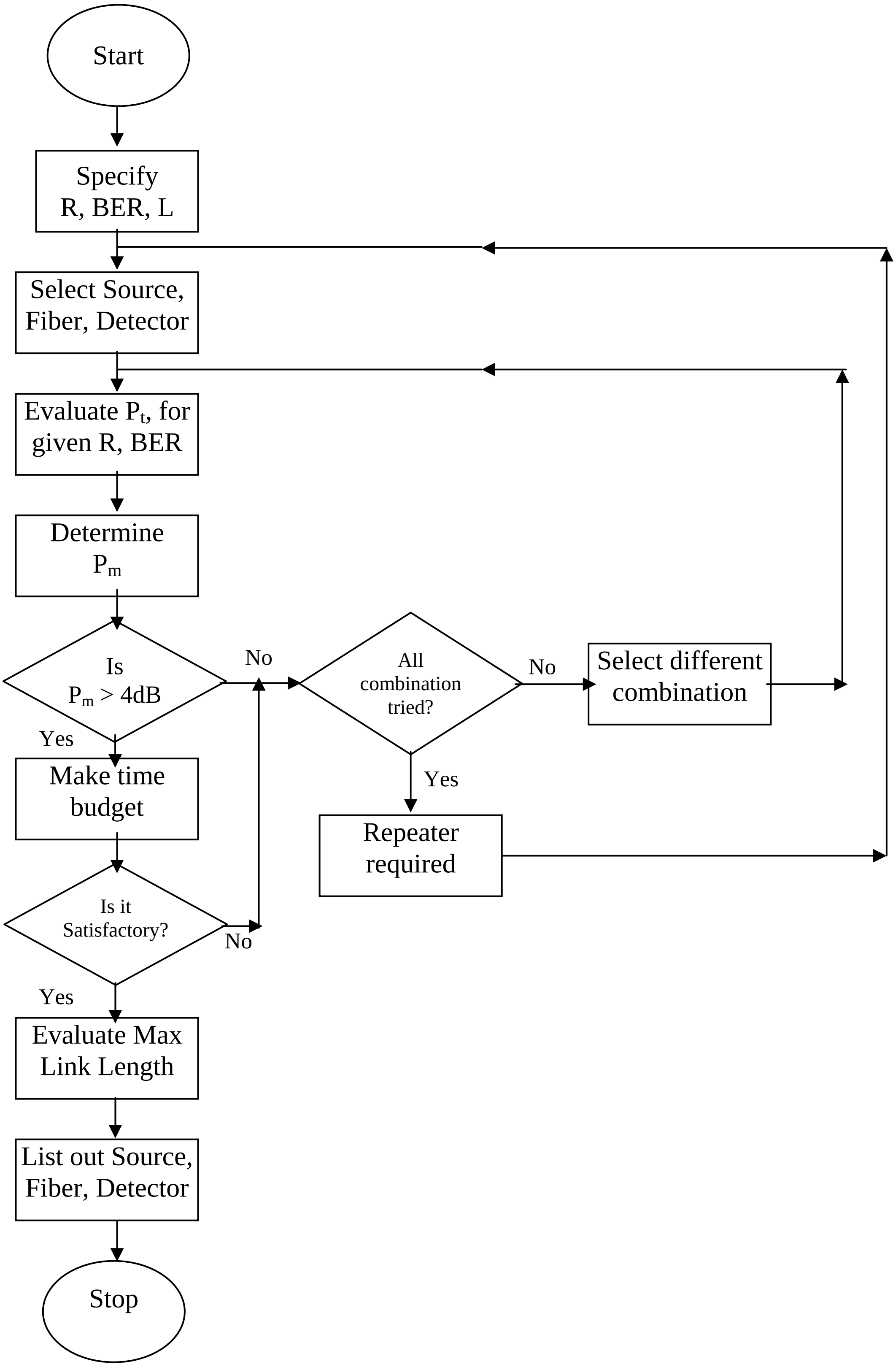


Fig. 2.2: Flow chart of a fiber optic link design.

2.4.1 Requirements in the Link Design

The key system requirements needed in the link design are:

a) Data or Bit rate/ Bandwidth;
b) Bit error rate (BER) / Signal-to-noise Ratio (SNR) and
c) Transmission distance or link length.

In the optical fiber communication link design the basic issues are:

a) Attenuation, which determines the power available at the photodetector input for a given source power (known as power budget) and
b) Dispersion, which determines the limiting data rate usable bandwidth (known as time budget) [15].

2.4.2 Power Budget

The amount of optical power launched into a given fiber by a given transmitter depends on the nature of its active optical source (LED or Laser Diode) and the type of fiber, including such parameters as core diameter and numerical aperture. Manufacturers sometimes specify an optical power budget only for a fiber that is optimum for their equipment or specify only that their equipment will operate over a given distance, without mentioning the fiber characteristics. The purpose of the power budget is to ensure that enough power will reach the receiver to maintain reliable performance during the entire system lifetime.

Performance of the system is evaluated by analyzing the link power budget of the system and the cost is kept minimum by carefully selecting the system components from a variety of available choices [15].

2.5 Major Components of Optical Links

2.5.1 Optical Sources

In most optical communication systems, semiconductor light sources are used to convert electrical signals into light. Optical sources for wireless transmission must be compatible to overcome the atmospheric effects and they should be such that one can easily modulate the light directly at high data rates. Generally either LASERs or LEDs are used in optical communication systems.

Typical line widths of common sources are listed in Table 2.2. This conversion between spectral width in wavelengths $\Delta\lambda$ and bandwidth in frequency Δf is

$$\frac{\Delta f}{f} = \frac{\Delta\lambda}{\lambda}$$

where, f is the center frequency, λ is the center wavelength, and Δf is the range of frequencies radiated. This conversion is simply the mathematical statement that the fractional emission width is the same whether computed on the basis of wavelength spread or frequency spread.

Table 2.2: Typical Spectral Widths

Source	Linewidth ($\Delta\lambda$) nm
Light-emitting diode	20-100
Laser diode	1-5
Nd: YAG laser	0.1
HeNe laser	0.002

2.5.1.1 Light Emitting Diode (LED)

Light emitting diodes (LEDs) used in optical communication systems are the same as visual display LEDs except that they operate in the infra-red region and with many times higher intensity of emission. When the p-n junction is forward biased, photon emission takes place due to the recombination of electron-hole pair. The wavelength of emission will depend on the energy gap.

2.5.1.2 LASER

LASER stands for “Light Amplification by Stimulating Emission of Radiation”. Compared to LED, a LASER has wider bandwidth, higher power output, higher modulation efficiency, narrower spectral linewidth and narrower emission pattern. LASER sources are much brighter than LEDs. LASER action is the result of three key processes [16]. These are photon absorption, spontaneous emission and stimulated emission. These three processes are represented by the simple two energy-level diagrams in Fig. 2.3, where E_1 is the ground-state energy and E_2 is the excited state energy.

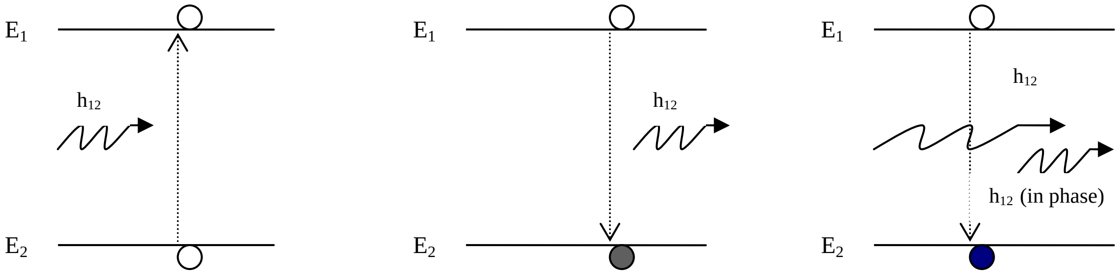


Fig. 2.3: The three keys transition process involved in laser action.

The open circle represents the initial state of the electron and the heavy dot represents the final state. Incident photons are shown on the left of each diagram and emitted photons are shown on the right.

According to Planck's law, a transition between these two states involves the absorption or emission of a photon energy $h\upsilon_{12} = E_2 - E_1$. Normally, the system is in the ground state. When a photon of energy $h\upsilon_{12}$ impinges on the system, an electron in state E_1 can absorb the photon energy and be excited to state E_2 and is called absorption. Since this is an unstable state, the electron will shortly return to the ground state, thereby emitting a photon of energy $h\upsilon_{12}$. This occurs without any external stimulation and is called spontaneous emission. The emissions are isotropic and of random phase and, thus, appear as a narrowband Gaussian output. When a photon of energy $h\upsilon_{12}$ impinges on the system while the electron is in excited state, the electron is immediately stimulated to drop to the ground state and give off a photon of energy $h\upsilon_{12}$. This emitted photon is in phase with the incident photon and the resultant emission is known as stimulated emission.

In thermal equilibrium, the density of excited electrons is very small. Most photons incident on the system will, therefore, be absorbed, so that stimulated emission is essentially negligible. Stimulated emission will exceed absorption only if the population of the excited states is greater than that of ground state. This condition is called population inversion. Since this is not an equilibrium condition, population inversion is achieved by various "pumping" techniques. In a semiconductor laser, population inversion is accomplished by injecting electrons into the material at the device contacts to fill the lower energy states of the conduction band. In solid-state lasers like the ruby laser or Neodymium laser, light from a powerful source is absorbed in the active medium and increases the population of a number of higher energy levels. In gas LASER's a similar metastable level is preferentially populated with the help of electronic excitation.

The results displayed in Table 2.3 (including data for a 1.3 µm LED system) dramatically illustrate the advantage of operating at the longer wavelengths and the superiority of the more coherent LASER diode over the LED fir high-rate-length applications. Systems using LASER diodes in the long-wavelength region are more complex and costlier than LED systems in the shorter-wavelength range 0.8-0.9 µm; so they are used only when necessary to achieve higher performance. The tabulated rates are fairly high. They will be lower in some systems because of additional pulse spreading caused by modal distortion.

Table 2.3: Information-Capacity Examples

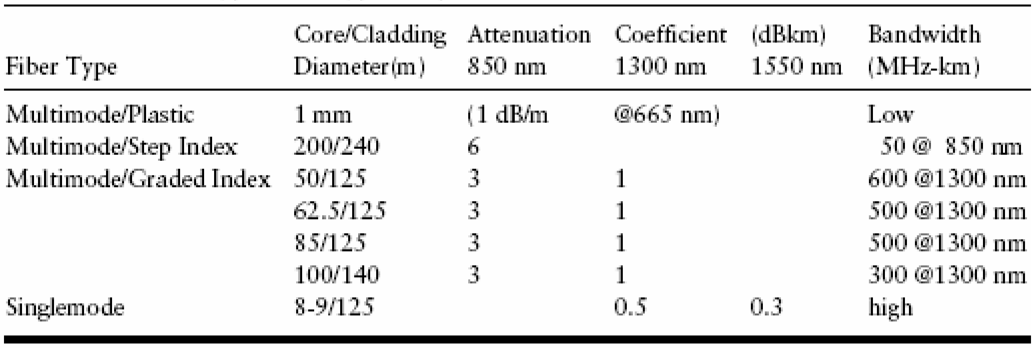
Source	λ **(µm)**	$\Delta\lambda$ **(nm)**	$\Delta(\tau / L)$ **(ns/km)**	**Optic** $f_{3-dB}xL$ **(Gbpsxkm)**	$R_{NRZ}xL$ **(Gbpsxkm)**	**Electrical** $f_{3-dB}xL$ **(Gbpsxkm)**	$R_{RZ}xL$ **(Gbpsxkm)**
LED	0.82	20	2.2	0.23	0.32	0.16	0.16
LED	1.5	50	0.75	0.67	0.94	0.47	0.47
LED	1.3	50	0.15	3.33	4.67	2.33	2.33
LD	0.82	1	0.11	4.55	6.4	3.2	3.2
LD	1.5	1	0.015	33.33	46.7	23.3	23.3

2.5.2 Optical Fiber

There are two basic types of optical fiber- multimode and single mode. Multimode fiber means that light can travel many different paths (called modes) through the core of the fiber, entering and leaving the fiber at various angles. The highest angle that light is accepted into the core of the fiber defines the numerical aperture (NA).

Two types of multimode fiber exist, distinguished by the index profile of their cores and how light travel in them (Table 2.4).

Table 2.4: Fiber types and typical specifications



Fiber Type	Core/Cladding Diameter(m)	Attenuation 850 nm	Coefficient 1300 nm	(dBkm) 1550 nm	Bandwidth (MHz-km)
Multimode/Plastic	1 mm	(1 dB/m	@665 nm)		Low
Multimode/Step Index	200/240	6			50 @ 850 nm
Multimode/Graded Index	50/125	3	1		600 @1300 nm
	62.5/125	3	1		500 @1300 nm
	85/125	3	1		500 @1300 nm
	100/140	3	1		300 @1300 nm
Singlemode	8-9/125		0.5	0.3	high

2.5.2.1 Single Mode Fiber (SMF)

Fiber with a core diameter less than about ten times the wavelength of the propagating light cannot be modeled using geometric optics. Instead, it must be analyzed as an electromagnetic structure, by solution of Maxwell's equations as reduced to the electromagnetic wave equation. The electromagnetic analysis may also be required to understand behaviors such as impair that occur when coherent light propagates in multi-mode fiber. As an optical waveguide, the fiber supports one or more confined transverse modes by which light can propagate along the fiber. Fiber supporting only one mode is called single-mode or mono-mode fiber. The behavior of larger-core multimode fiber can also be modeled using the wave equation, which shows that such fiber supports more than one mode of propagation (hence the name). The results of such modeling of multi-mode fiber approximately agree with the predictions of geometric optics, if the fiber core is large enough to support more than a few modes. The waveguide analysis shows that the light energy in the fiber is not completely confined in the core. Instead, especially in single-mode fibers, a significant fraction of the energy in the bound mode travels in the cladding as an evanescent wave.

The most common type of single-mode fiber in fig. 2.4 has a core diameter of 8 to 10 µm and is designed for use in the near infrared. The mode structure depends on the wavelength of the light used, so that this fiber actually supports a small number of additional modes at visible wavelengths. Multi-mode fiber, by comparison, is manufactured with core diameters as small as 50 microns and as large as hundreds of microns.

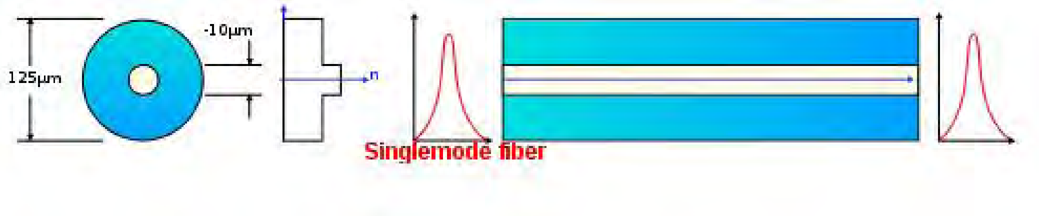


Fig. 2.4: Single mode fiber

Single mode fiber just shrinks the core size to a dimension about six times the wavelength of light traveling in the fiber and it has a smaller difference in the refractive index of the core and cladding, causing all the light to travel in only one mode. Thus modal dispersion disappears and the bandwidth of the fiber increases tremendously over graded-index fiber.

2.5.2.2 Multimode Fiber (MMF)

Fiber with large (greater than 10 µm) core diameter may be analyzed by geometric optics. Such fiber is called multimode fiber, from the electromagnetic analysis. In a step-index multimode fiber in fig 2.5, rays of light are guided along the fiber core by total internal reflection.

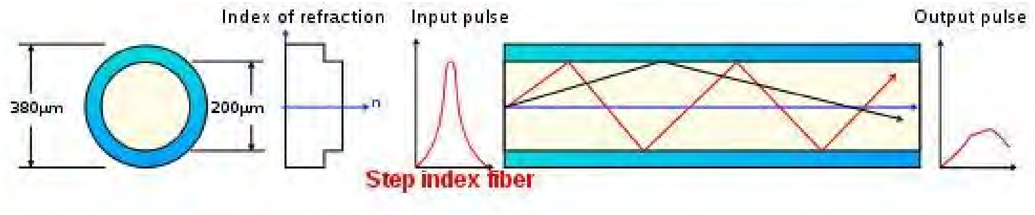


Fig. 2.5: Step Index Fiber

Rays that meet the core-cladding boundary at a high angle (measured relative to a line normal to the boundary), greater than the critical angle for this boundary, are completely reflected. The critical angle (minimum angle for total internal reflection) is determined by the difference in index of refraction between the core and cladding materials. Rays that meet the boundary at a low angle are refracted from the core into the cladding, and do not convey light and hence information along the fiber IS LOST. The critical angle determines the acceptance angle of the fiber, often reported as a numerical aperture. A high numerical aperture allows light to propagate down the fiber in rays both close to the axis and at various angles, allowing efficient coupling of light into the fiber. However, this high numerical aperture increases the amount of dispersion as rays at different angles have different path lengths and therefore take different times to traverse the fiber. A low numerical aperture may therefore be desirable.

Step-index multimode fiber has a core composed completely of one type of glass. Light travels in straight lines in the fiber, reflecting off the core/cladding interface. The NA is determined by the difference in the indices of refraction of the core and cladding and can be calculated by Snell’s law. Since each mode or angle of light travels a different path; a pulse of light is dispersed while traveling through the fiber, limiting the bandwidth of step-index fiber.

In graded-index multimode fiber in fig 2.6, the core is composed of many different layers of glass, chosen with indices of refraction to produce an index profile approximating a parabola, where from the center of the core the index of refraction gets lower toward the cladding.

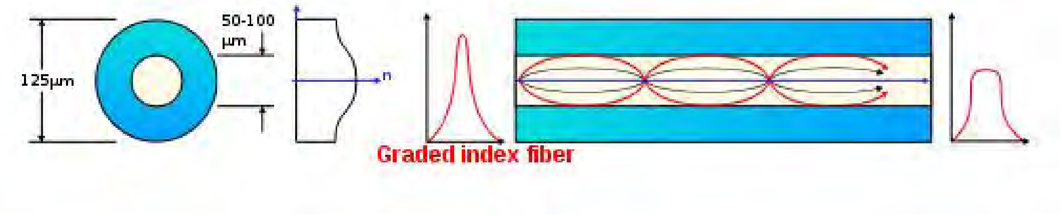


Fig. 2.6: Graded Index Fiber.

Since light travels faster in the lower index of refraction glass, the light will travel faster as it approaches the outside of the core. Likewise, the light traveling closest to the core center will travel the slowest. A properly constructed index profile will compensate for the different path lengths of each mode, increasing the bandwidth capacity of the fiber by as much as 100 times over that of step-index fiber.

In graded-index fiber, the index of refraction in the core decreases continuously between the axis and the cladding. This causes light rays to bend smoothly as they approach the cladding, rather than reflecting abruptly from the core-cladding boundary. The resulting curved paths reduce multi-path dispersion because high angle rays pass more through the lower-index periphery of the core, rather than the high-index center.

The index profile is chosen to minimize the difference in axial propagation speeds of the various rays in the fiber. This ideal index profile is very close to a parabolic relationship between the index and the distance from the axis.

2.5.2.3 Data sheet of different types of commercial optical fiber

In Table 2.5 we have complied representative numerical values of important properties for the various fibers introduced [16].

Table 2.5: Representative Characteristics of Commercial Fibers

Description	Core Diameter (μm)	NA	Loss (dB/km)	$\Delta(\tau / L)$ (ns/km)	$f_{3-dB} xL$ (MHzxkm)	Source	Wavelength (nm)
Multimode							
Glass							
SI	50	0.24	5	15	33	LED	850
GRIN	50	0.24	5	1	500	LD	850
GRIN	50	0.20	1	0.5	1000	LED,LD	1300
PCS							
SI	200	0.41	8	50	10	LED	800
Plastic							
SI	1000	0.48	200	-	-	LED	580
Singlemode							
Glass	5	0.10	4	< 0.5	> 1000	LD	850
Glass	10	0.10	0.5	0.006	83000	LD	1300
Glass	10	0.10	0.2	0.006	83000	LD	1550

Within each category, a number of designs have been commercially produced, so that somewhat different characteristics may be found when searching manufacturers’ literature for specific fibers.

In Table 2.6 the performance comparison of optical communication system of variety of commercial fibers at BER 10^{-10} is presented [17]. This table is useful as a guide.

Table 2.6: Performance comparison of optical communication system of variety of commercial fibers at BER 10^{-10}

Fiber Name	**Distance in kms at BER 10^{-10}**
DS_Normal	156
DS_Anomalous	246
Alcatel SMF_1550	105
Alcatel Teralight_1550	204
Corning LEAF	242
Corning LEAF_Submarine	242
Corning SMF28e_1550	103
Corning SMF28_1550	103
Furukawa SM332_1550	93
Lucent Allwave_1550	133
Lucent truewave_1550	228
Pirelli Deeplight_1550	208
Pirelli Freelight_1550	210
Pirelli Widelight_1550	155
Sumitomo ZPLUS_1550	78
Sumitomo Z_1550	97

As an aid in preliminary design, the characteristics of typical semiconductor light sources are listed in Table 2.7. At this point in the discussion we have enough information to select the carrier wavelength, the type of fiber, and the light source. LEDs can be used profitably with both multimode Step-Index or multimode Graded-Index fibers, but in different regions of the optic spectrum. In Step-Index fibers, modal distortion dominates. Materials dispersion, caused by the large spectral width of the LED, is smaller and can usually b neglected. Reducing the material dispersion further by selecting a laser diode serves no purpose.

Table 2.7: Typical Characteristics of Diode Light Sources

Property	**LED**	**Laser Diode**	**Single-mode Laser Diode**
Spectral Width (nm)	20-100	1-5	< 0.2
Rise time (ns)	2-250	0.1-1	0.05 – 1
Modulation bandwidth(MHz)	< 300	2000	6000
Coupling efficiency	Very low	Moderate	High
Compatible fiber	Multimode SI	Multimode GRIN	Single-mode
	Multimode GRIN	Single-mode	-
Temperature sensitivity	Low	High	High
Circuit complexity	Simple	Complex	Complex
Lifetime(hours)	10^5	10^4 - 10^5	10^4 - 10^5
Costs	Low	High	Highest
Primary use	Moderate paths	Long paths	Very long paths
	Moderate data- rates	High data-rates	Very high rates

For these reasons, LEDs are normally chosen for multimode Step-Index links. Systems using multimode Step-Index fibers and LED sources will probably remain in the first window (0.8 -0.9 µm), where component costs are low. LEDs radiating in the first window are not optimum for Graded-Index links, because material dispersion causes more pulse spreading than the fiber's modal distortion. The advantages of Graded-Index fiber are mostly lost with this combination of components. However, in the second window (near 1.3 µm) material dispersion becomes minimal, even with a Led source. A Graded-Index fiber and a LED operating in the long wavelength region can combine to produce a system transmitting moderately high data rates over fairly long distances.

Because of higher initial costs and increased circuit complexity, laser diodes are used only when necessary. For long, high capacity systems, they combine effectively with multimode Graded-Index fibers or single-mode fibers. These systems operate in the first or second window (Fig. 2.1), fiber losses are lower, allowing longer transmission paths. The largest rate-length products are achieved when a single-mode laser diode is matched with a single-mode fiber and operated in the low-loss, long-wavelength windows.

2.5.3 Optical Detectors

An optical detector is a photon (light) to electron converter. Avalanche photo-diode (APD) and positive intrinsic negative (PIN) diode are the most commonly used detectors. The most important thing of the optical communication system is that the spectral response of both the source and the detector must be same, otherwise efficiency will suffer.

2.5.3.1 PIN diode

PIN is the simplest optical detector. It is composed of an n^+ substrate, a lightly doped intrinsic region and a thin p zone. Operated with a reverse bias, mobile carriers leave the p-n junction producing a zone of moderate electric field on both sides of the junction into the intrinsic region. As it only lightly doped, this field extends deeply. Incident light power is mainly absorbed in the intrinsic region, causing electron hole pairs to be generated. These carriers are separated by the influence of the electric field in the intrinsic region and represent a reverse diode current that can be amplified.

2.5.3.2 Avalanche Photo Diode (APD)

It is the second popular type of photodetector and has the advantage of internally multiplying the primary detected photocurrent by avalanche process, thus increasing the signal detection sensitivity. However, some noises are also generated here.

The frequency response of both PIN and APD are similar, making them both suitable up to 1 GHz. The main advantage of APD over PIN diode is greater gain bandwidth product due to the inbuilt gain. Silica is the material used at short wavelength (< 1 nm), GE, InGaAsP and AlGaAsP becoming popular at the longer wavelength around 1.3 μm.

2.5.3.3 Characteristics of Avalanche Photodiode (APD) and PIN Photodiode

The detector in a fiber communication system will be either an avalanche or a PIN photodiode. The PIN device is cheaper, less sensitive to temperature, and requires lower reverse bias voltage than the APD. The speeds of the two devices are comparable, so the PIN diode is preferable in most systems. The APD gain is needed when the system is loss limited, as occurs for long-distance links.

Although a wide variety of detectors and detector characteristics exist, it is useful to consider the typical values of important photodiode parameters, as shown in Table 2.8.

Table 2.8 : Typical Characteristics of Junction Photodetectors

Material	Structure	Rise Time (ns)	Wavelength (nm)	Responsivity (A/W)	Dark Current (nA)	Gain
Silicon	PIN	0.5	300-1100	0.5	1	1
Germanium	PIN	0.1	500-1800	0.7	200	1
InGaAs	PIN	0.3	900-1700	0.6	10	1
Silicon	APD	0.5	400-1000	75	15	150
Germanium	APD	1	1000-1600	35	700	50
InGaAs	APD	0.25	1000-1700	12	100	20

The responsivity given in the table is representative of the value at a wavelength where the detector might be used – that is, near 0.8 µm for silicon and near 1.3 or 1.5 µm for germanium and InGaAs.

Some of the information we have gathered on sources, fibers, and detectors is summarized in Fig. 2.7. An initial choice matched component can be made from this Fig. 2.7. This Fig. 2.7 illustrates the many decisions the system designer must take.

This include operating wavelength (visible, first, second and third window); light source (LED or LASER diode); fiber material (Glass, PCS, or Plastic); fiber type (Step-index, Graded-index, or Single-mode); and photodetector (PIN or APD).

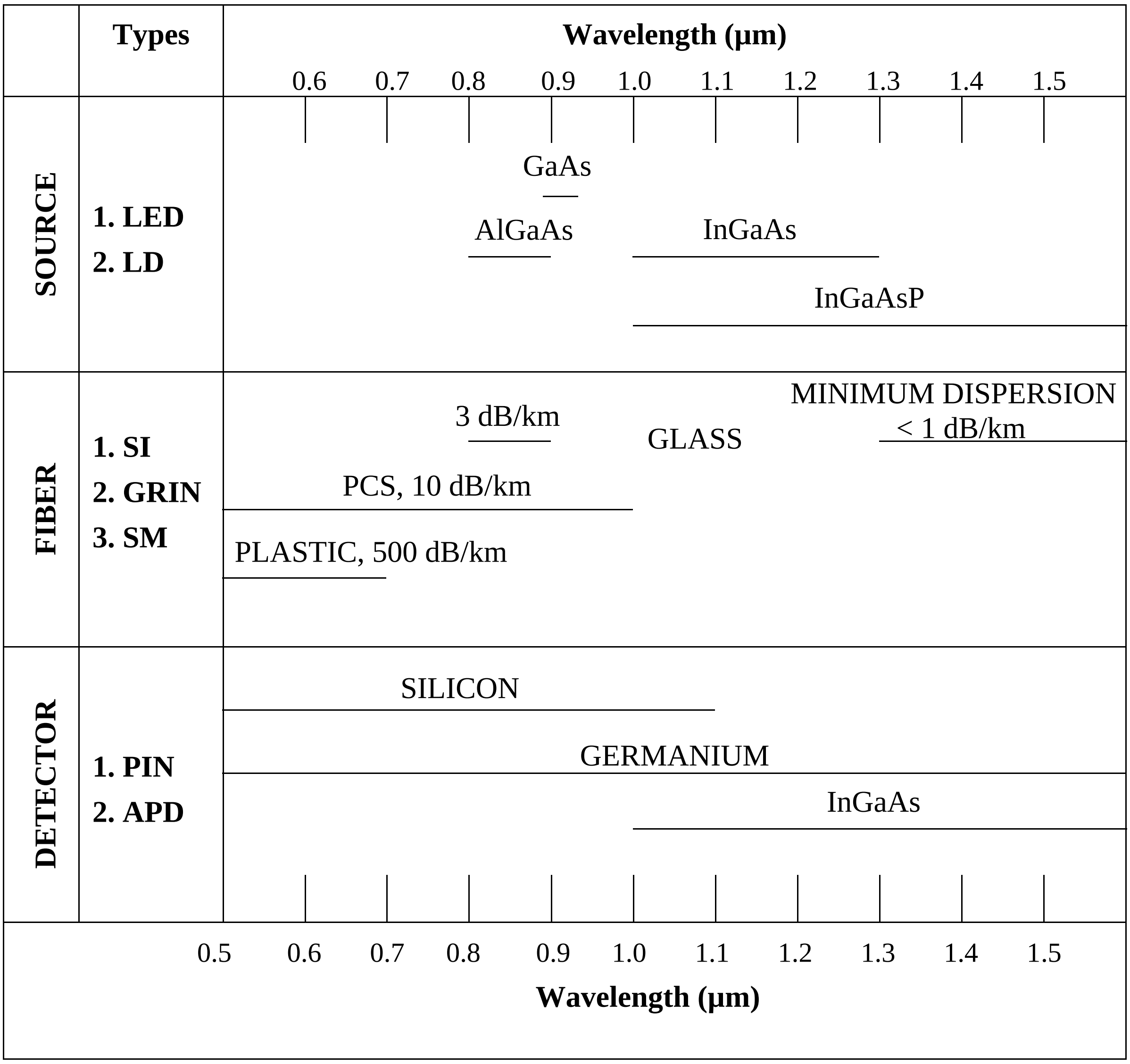


Fig. 2.7: Major Components of an Optical Fiber Communication System

2.5.4 Optical Amplifiers

The optical amplifiers play a vital role in today’s DWDM metro core networks and metro access networks in some cases. The generic requirements for the optical amplifiers used in metro space include superior optical performance, small size, low cost, low power consumption, and intelligence provided by embedded firmware and integrated control electronics [18]. There are two kinds of optical amplifiers used in the metro networks to meet the evolving networking demands: broadband optical amplifiers banded optical amplifiers, and single-channel optical amplifiers. Currently different kinds of optical amplifiers, such as ultra-compact EDFA, and SOA, are developed to target on the metro market.

2.5.4.1 Erbium-Doped Fiber Amplifier (EDFA)

The erbium-doped fiber amplifier (EDFA) is the most deployed fiber amplifier as its amplification window coincides with the third transmission window of silica-based optical fiber. Two bands have developed in the third transmission window - the *Conventional*, or C-band, from approximately 1525 nm - 1565 nm, and the *Long*, or L-band, from approximately 1570 nm to 1610 nm. Both of these bands can be amplified by EDFAs, but it is normal to use two different amplifiers, each optimized for one of the bands.

The principal difference between C- and L-band amplifiers is that a longer length of doped fiber is used in L-band amplifiers. The longer length of fiber allows a lower inversion level to be used, thereby giving at longer wavelengths (due to the band-structure of Erbium in silica) while still providing a useful amount of gain. EDFAs have two commonly-used pumping bands - 980 nm and 1480 nm. The 980 nm band has a higher absorption cross-section and is generally used where low-noise performance is required.

2.5.4.2 Semiconductor Optical Amplifier (SOA)

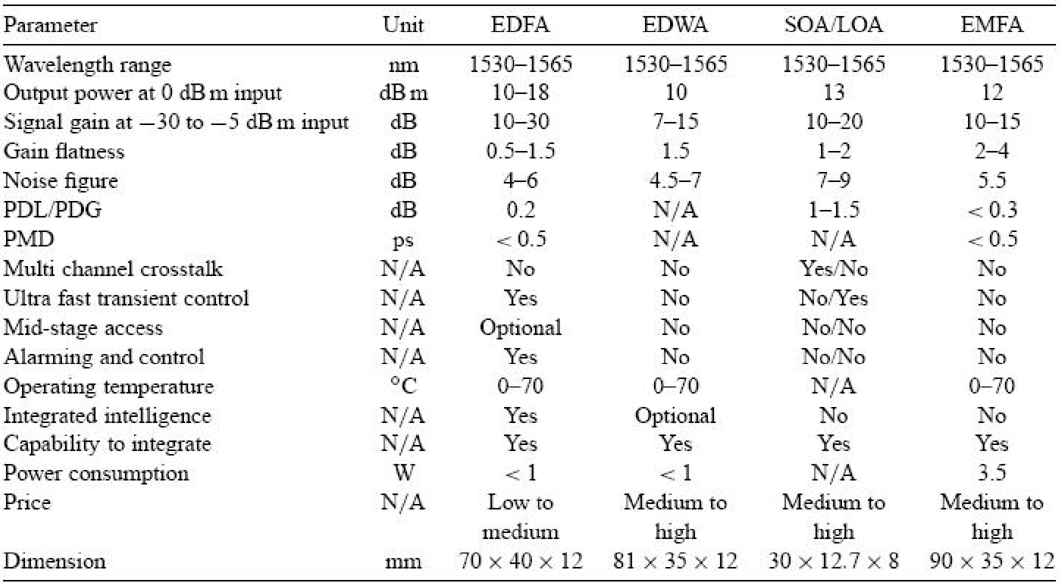
Semiconductor optical amplifiers are amplifiers which use a semiconductor to provide the gain medium. These amplifiers have a similar structure to Fabry-Pérot laser diodes but with anti-reflection design elements at the endfaces. Since this creates a loss of power from the cavity which is greater than the gain it prevents the amplifier from acting as a laser.

Semiconductor optical amplifiers are typically made from group III-V compound semiconductors such as GaAs/AlGaAs, InP/InGaAs, InP/InGaAsP and InP/InAlGaAs, though any direct band gap semiconductors such as II-VI could conceivably be used. Such amplifiers are often used in telecommunication systems in the form of fiber-pigtailed components, operating at signal wavelengths between 0.85 µm and 1.6 µm and generating gains of up to 30 dB.

The semiconductor optical amplifier is of small size and electrically pumped. It can be potentially less expensive than the EDFA and can be integrated with semiconductor lasers, modulators, etc. However, the performance is still not comparable with the EDFA. The SOA has higher noise, lower gain, moderate polarization dependence and high nonlinearity with fast transient time. This originates from the short nanosecond or less upper state lifetime, so that the gain reacts rapidly to changes of pump or signal power and the changes of gain also cause phase changes which can distort the signals. This nonlinearity presents the most severe problem for optical communication applications. However it provides the possibility for gain in different wavelength regions from the EDFA. "Linear optical amplifiers" using gain-clamping techniques have been developed.

Although the SOA is the most compact optical amplifier with the standard 14-pin butterfly package in the marketplace, its acceptance among equipment suppliers will be quite slow due to the intrinsic drawbacks of large polarization dependent gain, nonlinear crosstalk for multi channel applications, low output power level, and high noise figure. Table 2.9 lists the major characteristics of compact optical amplifiers based on the datasheets on the marketplace [18].

Table 2.9 : Comparison of typical parameters of compact optical amplifiers



Parameter	Unit	EDFA	EDWA	SOA/LOA	EMFA
Wavelength range	nm	1530–1565	1530–1565	1530–1565	1530–1565
Output power at 0 dBm input	dBm	10–18	10	13	12
Signal gain at −30 to −5 dBm input	dB	10–30	7–15	10–20	10–15
Gain flatness	dB	0.5–1.5	1.5	1–2	2–4
Noise figure	dB	4–6	4.5–7	7–9	5.5
PDL/PDG	dB	0.2	N/A	1–1.5	< 0.3
PMD	ps	< 0.5	N/A	N/A	< 0.5
Multi channel crosstalk	N/A	No	No	Yes/No	No
Ultra fast transient control	N/A	Yes	No	No/Yes	No
Mid-stage access	N/A	Optional	No	No/No	No
Alarming and control	N/A	Yes	No	No/No	No
Operating temperature	°C	0–70	0–70	N/A	0–70
Integrated intelligence	N/A	Yes	Optional	No	No
Capability to integrate	N/A	Yes	Yes	Yes	Yes
Power consumption	W	< 1	< 1	N/A	3.5
Price	N/A	Low to medium	Medium to high	Medium to high	Medium to high
Dimension	mm	70 × 40 × 12	81 × 35 × 12	30 × 12.7 × 8	90 × 35 × 12

2.6 Different Losses in Optical Fibers and their Characteristics

The attenuation of light in optical fibers as it propagates through the fiber is an important consideration in the design of optical transmission links since it determines the maximum repeaterless transmission distance between the transmitter and receiver.

The unit of attenuation (fiber loss) is defined as the ration of the optical output power P_{out} from a fiber of length L Km to the input power P_{in} and is expressed by α as :

$$\alpha L = 10 \log (P_{in}/P_{out}) \text{ dB} \tag{2.1}$$

The loss of fiber in dB/km is then expressed by,

$$\alpha = 10 \log (P_{in}/P_{out})/L \tag{2.2}$$

The losses in an optical fiber consist of the following:

(i) Coupling losses between the source –fiber , fiber-fiber and fiber-detector
(ii) Fiber bending losses
(iii) Losses due to absorption, scattering and radiation losses.

The first two types of losses are extrinsic in nature and may be reduced by taking various precautions. However, the losses due to scattering, absorption and radiation depend on some characteristics of the fiber (Fig. 2.1).

Absorption in optical fibers : Absorption of light in optical fibers may be intrinsic or extrinsic. Intrinsic absorption is due to material absorption and electron absorption. The extrinsic absorption is due to the presence of transition metal impurities known as impurity absorption.

Intrinsic Absorption : Material absorption is a loss mechanism related to the material composition and the fabrication process for the fiber which results in the dissipation of some of the transmitted optical power into heat in the optical fiber. An absolutely pure silicate glass has little intrinsic absorption due to its basic material structure in the near infra-red region. However, it has two intrinsic loss mechanism with low intrinsic absorption window over 0.8 μm to 1.7 μm range as shown in Fig. It may be observed that there is a fundamental absorption edge with peak in the ultra-violet region. In the ultra-violet region, light is absorbed as photons excite electrons in the core atom to a higher energy state. In silica fibers, the absorption peak occurs in the ultra-violet region at about 0.14 μm; however, the tail of this peak extends through to about 1 μm.

In the infra-red and far-infrared region, the atomic bonds associated with the core material absorb long wavelength light (material absortion). The absorption mechanism causes vibration of the molecules of the core materials and give absorption peaks at about 7 μm. The strong absorption bands occur due to oscillations of molecules such as Si-O (9.2 μm), P–O (8.1 μm), B–O (7.2 μm) and Ge–O (11.0 μm). The tails of the absorption mechanism is significant at or above 1.5 μm and is the cause of the most of the pure glass losses. The effect of both these processes may be minimized by suitable composition of core and cladding materials. Fibers made of flouride glasses, for example ZF_{4}, have low losses at higher wavelengths.

Extrinsic absorption : In practical optical fibers prepared by conventional melting techniques, a major source of signal attenuation is extrinsic absorption due to impurities of transition metal ions and water. It may be noted that certain of these impurities such as Chromium and Copper, can cause attenuation in excess of 1 dB/km in the near infra-red region. The transition metal contamination may be reduced to acceptable levels (one part in 10^{10}) by glass refining techniques such as vapour-phase oxidation which largely eliminates the effects of these metallic impurities.

Linear Scattering losses : Linear scattering mechanisms cause the transfer of some or all of the optical power contained within one propagating mode to be transferred linearly (in proportion to the power of the mode) into a different mode This process tends to result in attenuation of the transmitted light as the transfer may be to a leaky or radiation mode which does not continue to propagate within the fiber core but is radiated from the fiber. As the process is linear there is no change in frequency due to scattering. Linear scattering may be of two types; viz. Rayleigh and Mie scattering. Both result from the non-ideal physical properties of the manufactured fiber and is difficult and in some cases impossible to eradicate.

Nonlinear Scattering losses :

Optical waveguides do not always behave as completely linear channels whose increase in output optical power is directly proportional to the input optical power. Several nonlinear effects occur usually at high optical power levels. The nonlinear scattering causes transfer of optical power from one mode to the same or other mode in either the forward or backward direction at a different frequency. It depends on the power density within the fiber and becomes significant above threshold power levels. The most important types of nonlinear scattering in optical fiber are stimulated Brillouin scattering (SBS) and stimulated Raman scattering both of which are observed in SM fibers at high optical power densities.

Stimulated Brillouin Scattering: It may be regarded as the modulation of light through thermal molecular vibrations within the fiber and scattered light appear as upper and lower sidebands which are separated from the frequency of the incident light by the modulation frequency. The incident photon in this process produces a phonon of acoustic frequency as well as a scattered photon of different frequency. This produces an optical frequency shift which varies with the scattering angle because the frequency of the sound wave varies with the acoustic wavelength. The frequency is a maximum in the backward direction and reduces to zero in the forward direction making SBS a backward process. The threshold power of SBS is given by,

$$P_B = 4.4 \times 10^{-3} d^2 \lambda^2 \alpha_{dB} \nu \text{ watts} \quad (2.3)$$

where, d and λ are the fiber core diameter and the operating wavelength both measured in microns, α_{dB} is the fiber attenuation in decibels per km and ν is the source bandwidth in gigahertz.

Stimulated Raman Scattering : It is similar to SBS except that a high frequency optical phonon rather than an acoustic phonon is generated in the scattering process. Also SRS can occur both in the forward and backward directions in an optical fiber and may have an optical power threshold of up to three orders of magnitude higher than SBS threshold in a particular fiber. The threshold power for SRS is given by,

$$P_R = 5.9 \times 10^{-2} d^2 \lambda \alpha_{dB} \text{ watts} \quad (2.4)$$

where, d, λ , and α_{dB} are as specified for SBS.

2.7 Dispersion in Optical Fibers

Dispersion in optical fibers occurs due to dependence of the propagation phase constant and the refractive index of the core material on the transmitted wavelengths. The different wavelengths propagate at different velocities and results in dispersion of the output pulse shape in time. The mechanism of dispersion in different types of fiber is shown in Fig. 2.8.

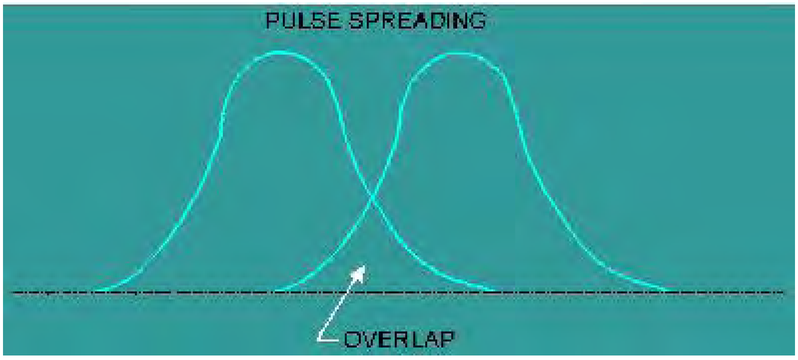


Fig. 2.8: Intramodal dispersion

In multi-mode fibers, dispersion is also caused by the different propagation time for the different modes which is called modal or inter-modal dispersion.

Dispersion in optical fibers can be classified into two major types:

(i) Intramodal dispersion; and (ii) Inter-modal dispersion

Intramodal Dispersion :

Intramodal dispersion : Intramodal dispersion is of types viz.

(i) Material dispersion; (ii) Waveguide dispersion.

The material dispersion coefficient $D_{mat} = M$ is defined as

$$D_{mat} = M = (\lambda/c)\ \left| d^2 n_1/d\lambda^2 \right| \qquad (2.5)$$

which is the dispersion in time (ps) for unit length of fiber (Km) and unit spectral width (nm) of the optical source. The unit of D_{mat} is thus ps/Km-nm.

The variations of different intramodal dispersions are shown in Fig. 2.9.

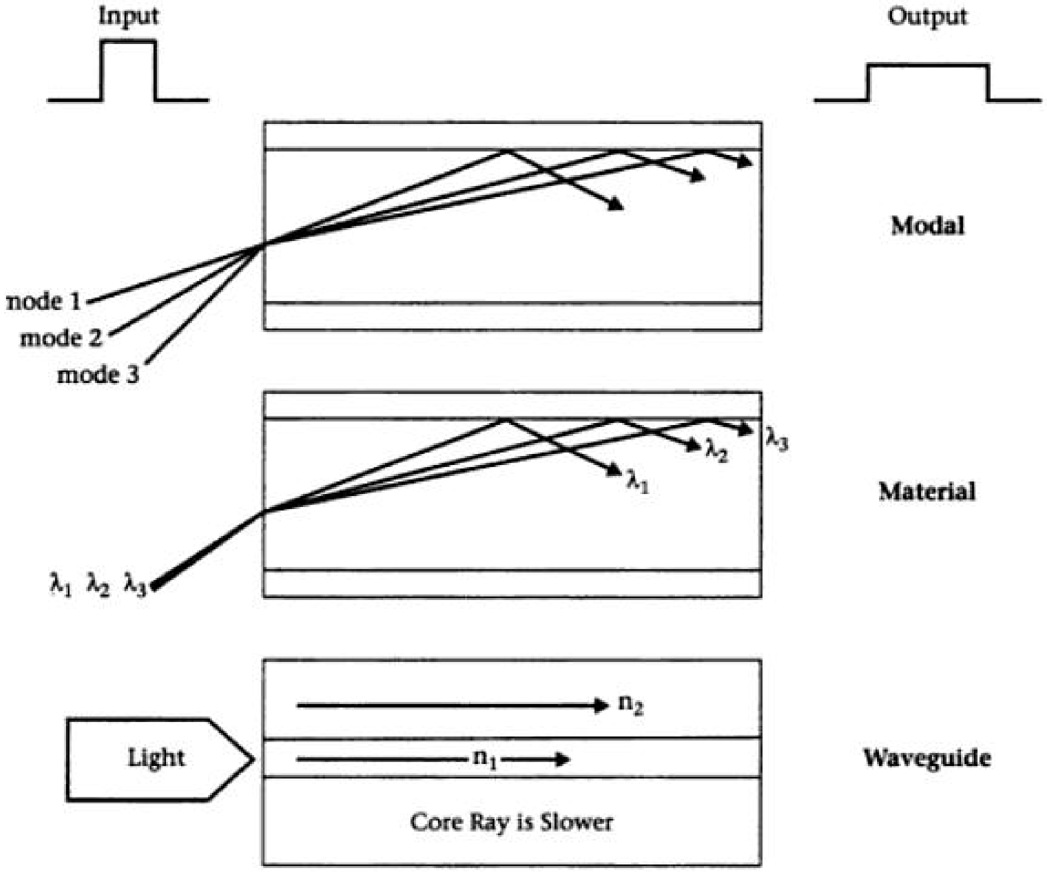


Fig. 2.9: Variations of different Intramodal dispersions

Intermodal Dispersion:

In multi-mode fibers, different modes travel at different group velocities and the output pulse width is dependant on the transmission times of the slowest and fastest modes. Multi-mode step-index fibers exhibit a large amount of intermodal dispersion which gives the greatest pulse broadening. However, intermodal dispersion in MM fibers may be reduced by adoption of an optimum refractive index profile which is provided by m=near parabolic profile of most graded index fibers. Hence, the overall pulse broadening in graded index fibers is much less than that in MM step index fibers (typically by a factor of 100).Thus Graded index MM fibers offer a tremendous bandwidth advantage over MM step index fibers. Under pure SM operation, there is no inter-modal dispersion and pulse broadening is solely due to intra-modal dispersion.

The delay between the transmit times of the two rays i.e. the delay difference is given by

$$\delta T_s = T_{\max} - T_{\min} = Ln_1^{\ 2} / cn_2 - Ln_1 / c = Ln_1^{\ 2} / cn_2[(n_1 - n_2)/n_1] = Ln_1^{\ 2}\Delta / cn_2 \quad (2.6)$$

where Δ is the relative refractive index difference.

Writing $n_{12} \approx n_1 n_2$ then

$$\delta T_s = Ln_1\Delta / c = L(NA)^2 / 2n_1 c \text{ as } NA = n_1(2\Delta)^{1/2} \quad (2.7)$$

The rms pulse broadening at the fiber output due to inter-modal dispersion for the MM step-index fiber is given by the standard deviation σ_s which is the square root of the variance σ_s^2 given by

$$\sigma_s^{\ 2} = \int_{-\alpha}^{\alpha} t^2 p(t)dt = \int_{-\delta T_s/2}^{\delta T_s/2} t^2 (\frac{1}{\delta T_s})dt \quad (2.8)$$

Integration gives $$\sigma_s^{\ 2} = (1/3)(\delta T_s/2)^2 \quad (2.9)$$

And σ_s is given by $$\sigma_s = Ln_1\Delta / 2\sqrt{3}c = L(NA)^2 / 4\sqrt{3}n_1 c \quad (2.10)$$

Overall Dispersion:

The overall rms pulse width at the output of a multimode fiber is due to intra-modal and intermodal dispersion and can be expressed as,

$$\sigma^2 = \sigma_{\text{intra}}^{\ 2} + \sigma_{\text{inter}}^{\ 2} \quad (2.11)$$

2.8 Effect of Dispersion on Bandwidth of Optical Fibers

For a input rectangular pulse, the output pulse is Gaussian which can be expressed as,

$$h(t) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-t^2/2\sigma^2} \tag{2.12}$$

The Fourier transform of the output pulse shape h(t) is given by,

$$H(f) = e^{-\omega^2\sigma^2/2}$$

At -3dB optical frequency,

$$f_o = \frac{H(f_0)}{H(0)} = 0.5 \tag{2.13}$$

$$\Rightarrow e^{-\omega_0{}^2\sigma^2/2} = 0.5$$

$$\Rightarrow \omega_0{}^2\sigma^2 = 2\ln(2)$$

$$\Rightarrow \omega_0 = \sqrt{2\ln(2)/\sigma}$$

$$\Rightarrow \omega_0 = 1.18/\sigma$$

$$\Rightarrow f_0(-3dB) = 0.187/\sigma$$

Thus the bandwidth of a dispersive fiber is given by,

B_{opt} = 0.187/(rms pulse width) $\cong 0.2/\sigma$

Maximum Bit rate in a dispersive fiber :

For Return to zero (RZ) data, the maximum transmission rate B_T is given by,

B_T (max) =bits/cycle x cycle/sec = 1 x B_{opt} = B_{opt}

For non-return to zero (NRZ) data, the maximum transmission rate B_T is given by,

B_T (max) =bits/cycle x cycle/sec = 2 x B_{opt} = $2B_{opt}$

2.9 Optical Transmission System

Parameters to be considered,

(i) Transmission Rate;
(ii) Signal Type (RZ/NRZ);
(iii) Transmission Path length (link distance);
(iv) Regenerator requirement;
(v) Connector and splicing requirements;
(vi) System operating temperature;
(vii) Probability of bit error (Pe).

Optical Link Design :

(i) Power Budget design and
(ii) Bandwidth (rise time) Budget design

Power Budget :

$$P_T - (L_{cp} + L_{ct} + L_{sp} + L_f) - M > R_s \tag{2.14}$$

Where,

P_T = Transmitter power (output of light source) in dBm;
L_{cp} = Coupling losses between the light source and the fiber core in dB;
L_{ct} = Connector losses (including light source and photodiode) in dB;
L_{sp} = Splicing losses in dB;
L_f = Fiber attenuation in dB;
M = System loss margin requirement (specification) in dB and
R_s = Receiver sensitivity requirement (specification) in dBm.

Bandwidth (Risetime) Budget :

System transmission rate rise time :

$$\begin{aligned} R_{NRZ} &\le \frac{0.7}{t_s} \\ R_{RZ} &\le \frac{0.35}{t_s} \end{aligned} \tag{2.15}$$

Where,

R_{NRZ} = NRZ signaling rate (bps)
R_{RZ} = RZ signaling rate (bps)
t_s = Total system rise time

$$t_s^{\,2} = t_{tx}^{\,2} + t_f^{\,2} + t_{rtx}^{\,2} \tag{2.16}$$

where,

t_x = Tx rise time
t_f = Fiber rise time
t_{rx} = Rx rise time

Fiber rise time :

(i) Material dispersion;
(ii) Waveguide dispersion and
(iii) Intermodal dispersion.

For SMF :

$$t_f = t_{smf} = \left|(M + W) * \Delta\lambda * L\right| \tag{2.17}$$

where,

M and W are the material and waveguide dispersion in ps/km-nm

Δλ = spectral width of the optical source in nm

L = fiber length in km

For Graded Index MMF :

$$\begin{aligned} & t_f^{\ 2} = t_{smf}^{\ 2} + t_d^{\ 2} \\ & \Rightarrow t_d = (n_1 - n_2)^2 /(2cn_1) * L \end{aligned} \tag{2.18}$$

For Step Index MMF :

$$t_d = n_1(n_1 - n_2)\ /(cn_2) * L \tag{2.19}$$

Photodiode Rise Time :

$$t_{pd} = (t_{tr}^{\ 2} + t_{ct}^{\ 2})^{1/2} = \left[\left(\frac{Depletionlayerwidth}{v}\right)^2 + \left(2.19R_L C_d\right)^2\right]^{1/2} \tag{2.20}$$

where,

t_{tr} = transit rise time and t_{ct} = circuit rise time

2.10 Optical Transmitters and Eye Safety

The wavelength band between approximately 780 and 950 nm is presently the best choice for most present applications of optical wireless links, due to the availability of low-cost LED’s and laser diodes (LD’s) and because it coincides with the peak responsivity of inexpensive, low-capacitance silicon photo diodes. The primary drawback of radiation in this band relates to eye safety i,e, it can pass through the human cornea and be focused by the lens onto the retina, where it can potentially induce thermal damage. The cornea is opaque to radiation at wavelength beyond approximately 1400 nm, considerably reducing potential ocular hazard, so that it has been suggested that the 1550-nm band may be better suited for optical wireless links. Unfortunately, the photo diodes presently available for this band, which are made of germanium of InGaAs, have much higher costs and capacitances per unit area than their silicon counterparts. To our knowledge, at present all commercially available systems operate in the shorter-wavelength band.

Table 2.10 presents a comparison between LED’s and LD’s. LED’s are currently used in all indoor commercial systems, due to their extremely low cost and because most LED’s emit light from a sufficiently large surface area that they are generally considered eye-safe. Typical packaged LED’s emit light into semi-angle (at half power) ranging from approximately 10–30 degrees, making them suitable for directed transmitters. Non-directed transmitter’s frequency employ multiple LED’s oriented in different directions.

Table 2.10: Comparison between LED’s and LD’s

Characteristics	LED	LD
Spectral width	25-100 nm (10-50 THz)	< 10^{-5} to 5 nm (<1 MHz to 2 THz)
Modulation Bandwidth	Tens of KHz to tens of MHz	Tens of KHz to tens of GHz
E/O Conversion Efficiency	10-20%	30-70%
Eye Safety	Generally considered eye-safe	Must be rendered eye-safe, Especially for $\lambda < 1400$ nm
Cost	Low	Moderate to high

Potential drawbacks of present LED’s include:

1) Typically poor electro-optic power conversion efficiencies of 10–20 % (though new devices have efficiencies as high as 40 %)
2) Modulation bandwidths that are limited to tens of MHz in typical low cost devices[2]
3) Broad spectral widths (typically 25–100 nm), which require the use of a wide receiver optical pass band, leading to poor rejection of ambient light and
4) The fact that wide modulation bandwidth is usually obtained at the expense of reduced electro-optic conversion efficiency.

LD’s are much more expensive than LED’s, but offer many nearly ideal characteristics:

1) electro-optic conversion efficiencies of 30–70 %,

2) wide modulation bandwidths, which range from hundreds of MHz to more than 10GHz and
3) Very narrow spectral widths (spectral widths ranging from several nm to well below 1 nm are available).

To achieve eye safety with an LD requires that one pass the laser output through some element that destroys its spatial coherence and spreads the radiation over a sufficiently extended emission aperture and emission angle. For example, one can employ a transmissive diffuser, such as a thin plate of translucent plastic. While such diffusers can achieve efficiencies of approximately 70 %, they typically yield a Lambertian radiation pattern, offering the designer little freedom to tailor the source radiation pattern. Computer-generated holograms offer a means to generate custom-tailored radiation patterns with efficiencies approaching 100 %, but must be fabricated with care to insure that any residual image of the LD emission aperture is tolerably weak.

The eye safety of infrared transmitters is governed by International Electro-technical Commission (IEC) standards. It is desirable for infrared transmitters to conform to the IEC Class 1 allowable exposure limit (AEL), implying that they are safe under all foreseen circumstances of use, and require no warning labels. At pulse repetition rates higher than 24 kHz, compliance with this AEL can be calculated on the basis of average emitted optical power alone. The AEL depends on the wavelength, diameter, and emission semiangle of the source. At present, the IEC is in the midst of revising the standards applying to infrared transmitters. Based on proposed revisions, at 875 nm, an IrDA-compliant source having an emission semiangle of 15 degrees and diameter of 1nm can emit an average power upto 28 mW. At the same wavelength, a Lambertian source (60 degrees semiangle) having a diameter of 1 nm can emit up to 280 mW; at larger diameters, the allowable power increases as the square of the diameter.

CHAPTER 3

CAPACITY FORECASTING FOR THE SUBMARINE CABLE NETWORK IN BANGLADESH

This chapter describes the capacity forecasting of the existing backbone network in Bangladesh. By making a comprehensive study on each operator's past and present growth, relative weighting factors are assigned for bandwidth demand of each application, and finally two forecasting equations are formulated by using MathLab software and carpeting the value of bandwidth. This equation is then used for bandwidth projection up to 2011 and beyond, and is compared with the available SMW-4 submarine cable capacity. Finally, redundancy of national and international backbone networks is recommended with appropriate topologies.

3.1 Capacity of Submarine Cable and Bandwidth Allocation for Bangladesh

Features of SEA-ME-WE-4 Submarine cable are given in below:

- The total length of SEA-ME-WE-4 submarine cable is 20,000 km;
- Two fiber pairs (One is called express pair and the other is omnibus pair);
- 64 wavelength per fiber pair, 10 Gbps per wavelength;
- Initial capacity 160 Gbps, Design capacity 1.28 terabit/sec.

Total route is divided into four segments (Refer to Figure 3.1).

- **Segment1 :** Singapore to Mumbai;
- **Segment2 :** Mumbai to Suez;
- **Segment3 :** Suez to Alexandria (land route cable through Egypt);
- **Segment4 :** Alexandria to Marseilles.

Fig. 3.1: SEA-ME-WE-4 Geographical Overview

Initially, Bangladesh owned a 10 Gbps capacity of submarine cable and all of it have been extended up to Dhaka, the capital of Bangladesh [19]. The block diagram of the existing submarine cable network in connection with the landing station at Cox's Bazar is shown in Fig. 3.2.

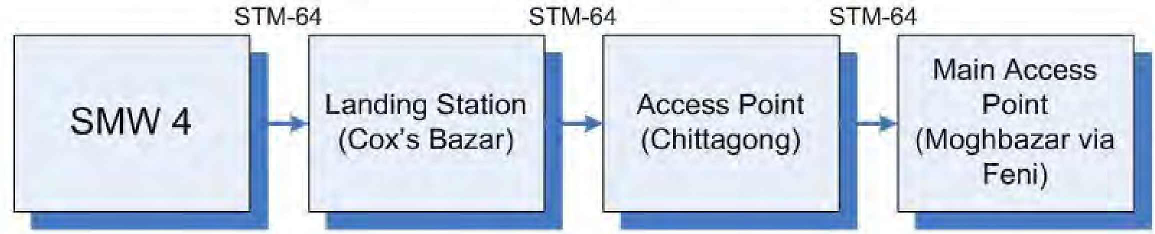


Fig. 3.2 : Schematic block diagram of the access network

The present capacity owned by Bangladesh is 24.12 Gbps [20]. However, because of lack of proper facilities and appropriate infrastructure, Bangladesh is yet to avail the full advantage of the submarine cable.

As discussed in this Chapter, total capacity of SMW 4 is 24.12 Gbps or 24,120 Mbps for Bangladesh. However, present available capacity is about 4.62 Gbps or 4620 Mbps. It needs further infrastructural development to increase the available capacity. Out of the total available capacity, 31% is allocated for data communication and 69% for voice communication, which is owned only by Bangladesh Telecom Company Limited (BTCL) formerly known as BTTB (refer to Fig. 3.3).

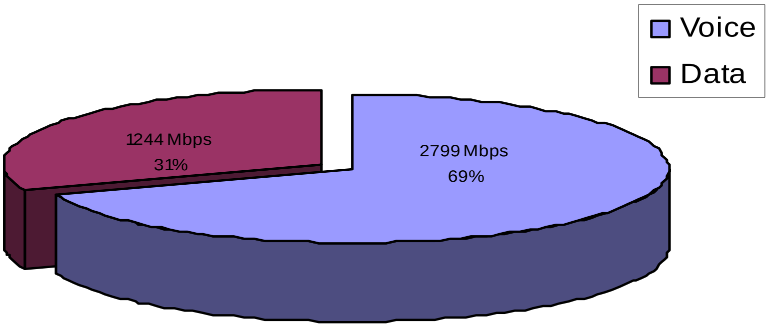


Fig. 3.3: Present bandwidth allocation of submarine cable capacity

A considerable amount of bandwidth will be used for overseas data communication services through International Private Leased Circuit (IPLC). IPLC has been defined as a dedicated secure digital point to point private connection between two locations (usually two LANs) in two different countries that allows transmission of data, large Internet packets, real-time video applications like video conferencing, and such other information communication services. The SEA-ME-WE-4 (SMW-4) submarine cable bandwidth acquired by the BTCL on ownership basis is for leasing out in the form of International Private Leasing Circuit (IPLC). These IPLCs are being used for providing mainly three services: voice, point-to-point data communication and Internet [20].

Fig.s' 3.3 and 3.4 are drawn from the data collected as part of the current study, which was intended to assess the need of bandwidth for Voice and Internet/Data services in Bangladesh. The present use of satellite bandwidth and its future need are shown in Table 3.1 and Fig. 3.4.

Table 3.1: Present and Projected Growth of Satellite Bandwidth

Present use (2007)		**Projected Use upto 2011**	
Voice	Data	Voice	Data
106	24	206	24

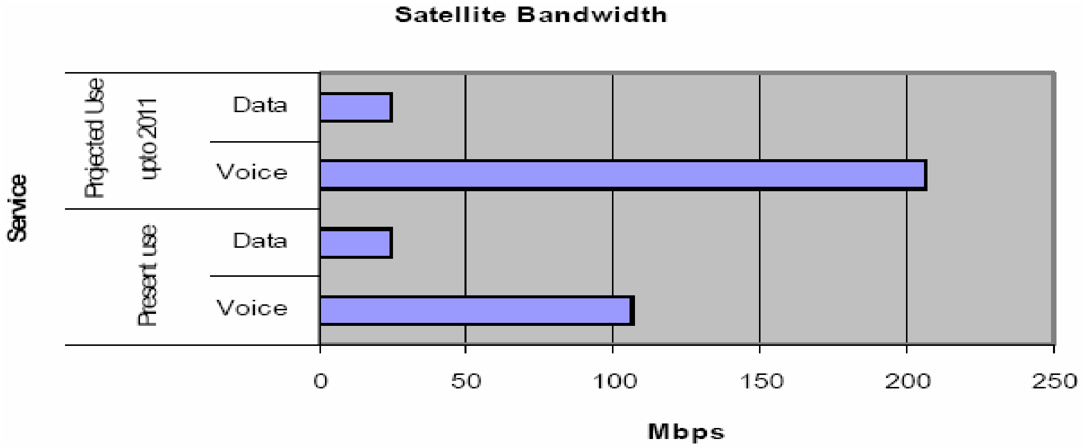


Fig. 3.4: Present and Projected Growth of Satellite Bandwidth

From Fig. 3.4, it is observed that at present 24/8 Mbps are allocated in data circuits, which is assumed to remain steady up to 2011. It is also assumed that bandwidth will increase to almost double from that of the present to 2011 in voice circuits.

The similar data for the SMW-4 submarine cable are shown in Table 3.2 and Fig. 3.5.

Table 3.2: Present and Projected Bandwidth of Submarine Cable

	Present use (2007)		**ILDTS implementation (2009)**		**Projected Use upto 2011**	
	Voice	Data	Voice	Data	Voice	Data
BTCL	2799	1244	3732	2177	5000	4354
IGW	-	-	3265.5	622	5000	1866

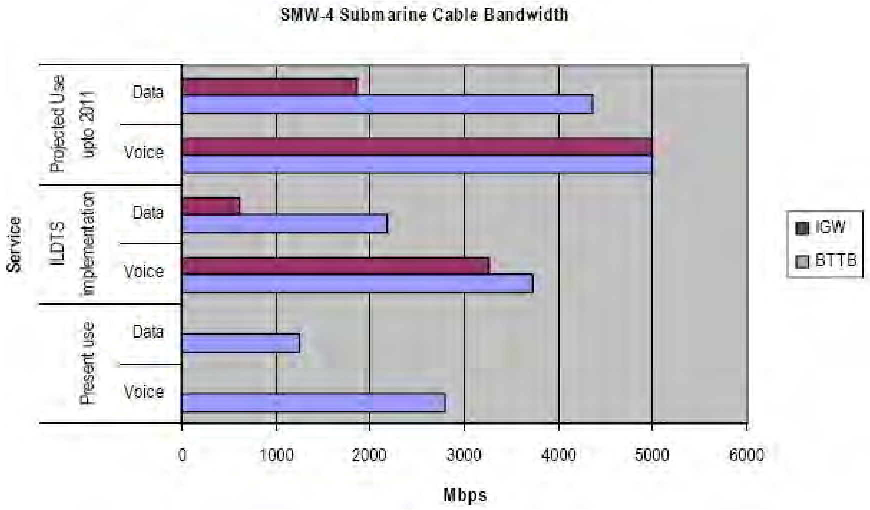


Fig. 3.5: Present and Projected Bandwidth of Submarine Cable

Source: Bangladesh Submarine Cable Company Limited

From Fig. 3.5, it is observed that present bandwidth allocation for data and voice circuits are 1244 Mbps and 2799 Mbps, respectively, which will almost double to 2799 Mbps and 6997.5 Mbps respectively after the implementation of the International Long Distance Telecom Services (ILDTS). Thus the bandwidth will increase almost 5 times more from the present 6220 Mbps to 10000 Mbps in 2011.

Out of the 40% available capacity (1866 Mbps), ISPs are allocated almost 99% of it for data communication and Internet connectivity. In contrast to the present allocation, ISPs of Bangladesh were using a 200 Mbps from the Satellite and VSATs. Thus it is noted that after the introduction of the submarine cable capacity, the bandwidth allocation of data connectivity has increased almost 9 times more than that of the previous satellite system.

3.2 Utilization of the available bandwidth

The available capacity (bandwidth) in SMW 4 submarine cable for Bangladesh is being used for three broad services: voice, data and Internet. As part of the current study, a survey has been carried out to Figure out the submarine cable capacity utilization in Bangladesh. Fig. 3.6 shows the bandwidth that has been registered by different user groups like Internet Service Providers (ISPs), mobile operators, universities, fixed phone operators, banks, IPLCs and others.

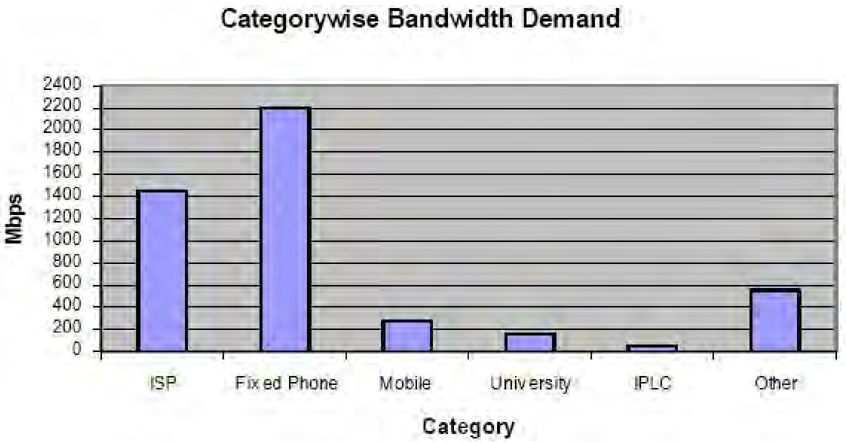


Fig. 3.6: Category-wise Bandwidth Demand

From Fig. 3.6, it can be seen that the maximum bandwidth is used by the ISPs and the fixed phone operators in Bangladesh and rest of the bandwidth are utilized by mobile operators, universities, banks and other organizations.

Till April’2008 21,965 voice circuits were available with 52 bilateral overseas voice operators through SMW-4 for international long distance voice communication. Before installation of the submarine cable, there were a few IPLCs having a total capacity not exceeding 512 Kbps via BTCL Satellite Earth Stations. But within the last 2 years, BTCL has leased out about 48 Mbps bandwidth for 35 IPLC connections. These are being used for corporate data communication. BTRC has recently started awarding licenses for Call Centre service. It has been made mandatory to establish overseas connectivity with call center clients through IPLC. The Internet backbone links have been increased to 12 STM-1 (1866 Mbps download + 1866 Mbps upload) equivalent capacities with various tier-1 ISPs in the Eastern and Western sides of the cable in April, 2008 [20].

As on April 2008, 105 leased line Internet connections are in service. These connections (using Fast/Gigabit Ethernet) have been given from Gulshan (Dhaka), Moghbazar (Dhaka) and Nandan Kanon (Chittagong) PoPs (Point-of-Presence) through optical fibers arranged by the customers. Among those, 87 connections are in Dhaka and 17 in Chittagong. It is notable that 5 corporate organizations and 6 universities now have optical connectivity [21]. It is noted that most of the PoPs are installed in Dhaka and Chittagong. Internet connections are mostly limited to Dhaka, Chittagong, Sylhet and Bogra.

The current study also includes the assessment of the existing and projected growth up to 2011 of the fixed phones, mobile phones and the Internet users in Bangladesh. The results of the study are shown in Fig. 3.7.

The results of the survey, that has been carried out as part of the study, reveal that the fixed phone subscribers’ growth in Bangladesh varies between 0.8 to 2 percent, whereas that of mobile phone varies between 2.5 to 5 percent monthly. However, it is now heading towards an almost steady level. Fig. 3.7 reveals that the fixed phones, mobile phones and Internet user growth are increasing dynamically in every year, and the growth of bandwidth utilization is steady.

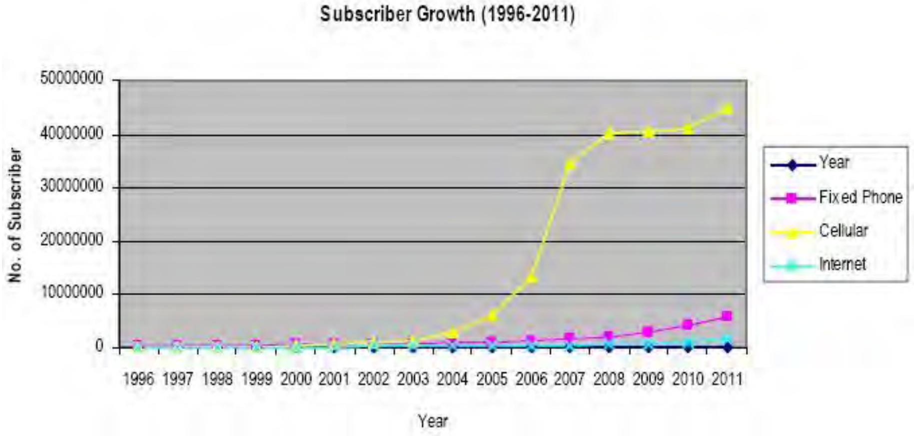


Fig. 3.7: Existing and projected growth of Fixed phone, Mobile phone and Internet users in Bangladesh

It is also mentioned that around 800 Mbps are utilized in voice circuits in Dhaka division and other 5 divisions together utilized 280 Mbps, whose owner is only BTCL. It is also observed that almost 50% bandwidth (1080 Mbps) is used of total allocation (2799 Mbps) in voice circuits. Therefore, the 50% unused bandwidth (1719 Mbps) can be used for different purposes like call centers, VoIP, ISP etc.

3.3 Prediction of Future Growth

An extensive study of the existing network is needed to survey the potential of the submarine cable, and to evaluate the requirements of different ISPs, call centers, software companies, mobile and fixed phone operators etc. In Bangladesh, we do not have specific plans based on the current demand and growth of the users of various telecommunications services. Therefore, extensive study is needed to forecast the future bandwidth demand for various telecommunications services.

At first, realistic data have been collected by a field survey. Using the realistic data, the total bandwidth requirement for each year is considered and a formula has been developed using the MathLab software by carpeting the value of bandwidth. The formula is represented by equation 3.1.

$$W = a + bW_P + cW_P^2 \tag{3.1}$$

where, W = next year's bandwidth; W_P = Bandwidth demand for the present year,

a = 245.36; b = 1.36; and c = 0.0000215.

This prediction gives a root mean square error of 6.9%. However, it does not include the effect of each type of telecommunication operator.

On the other hand, if we consider services of each individual telecom operators, like voice, data etc. for a year, the model would be more realistic. Therefore, using the MathLab software, another formula for predicting the bandwidth demand has also been developed, which is given by equation 3.2.

$$W = [(1+W_{VC})*W_{PVC} + (1+W_{IN})*W_{PIN} + (1+W_{MO})*W_{PMO} + (1+W_{NA})*W_{PNA}] \quad (3.2)$$

where,

W = Bandwidth demand of the following year
W_{VC} = factor for Voice Circuits = 0.60
W_{IN} = factor for Internet Bandwidth = 0.41
W_{MO} = factor for Mobile Operator = 0.49
W_{NA} = factor for other new applications = 1.00
W_{PVC} = Present bandwidth for Voice Circuits
W_{PIN} = Present bandwidth for Internet
W_{PMO} = Present bandwidth for Mobile Operators
W_{PNA} = Present bandwidth for other new applications

This prediction gives a root mean square error of 8.1%.

The main results of the survey that we carried out are also summarized below.

i. Voice Circuit (60% increase per year)
ii. Internet Bandwidth (41% increase per year)
iii. Mobile Operator (49% increase per year)
iv. Other new applications like IPLC, Call Center, Multi Media etc. (100% increase per year)

We have also calculated a yearly projected bandwidth for each telecommunication services considering the average increase in demand in two consecutive years, and finally computed the cumulative total projected bandwidth from the above facts obtained from the collected data.

The projected and formulated bandwidths are presented in Table 3.3(a) in terms of Mbps.

Table 3.3: Projected Bandwidth Capacity (in Mbps)

Service / year	Voice	Internet (1)	Mobile (2)	Other (3)	Data (1+2+3)	Projected total (Mbps)	Formulated (Mbps)	
							Eq. 3.1	Eq. 3.2
2005	622	311	116.625	38.875	466.5	1088.5	-	-
2006	1244	466.5	233.25	77.75	777.5	2021.5	1755	1684
2007	1866	622	350	155.5	1127.5	2993.5	3090	3150
2008	2488	933	505.375	272.125	1710.5	4198.5	4522	4696
2009	3732	1244	699.75	544.25	2488	6220	6352	6593
2010	6220	1555	933	1244	3732	9952	9565	9856
2011	9952	2480	1244	2488	5909	16164	15958	16022

The results of the yearly projected bandwidth are shown in Fig. 3.8, and those of the two predicted models are shown in Fig.3.9.

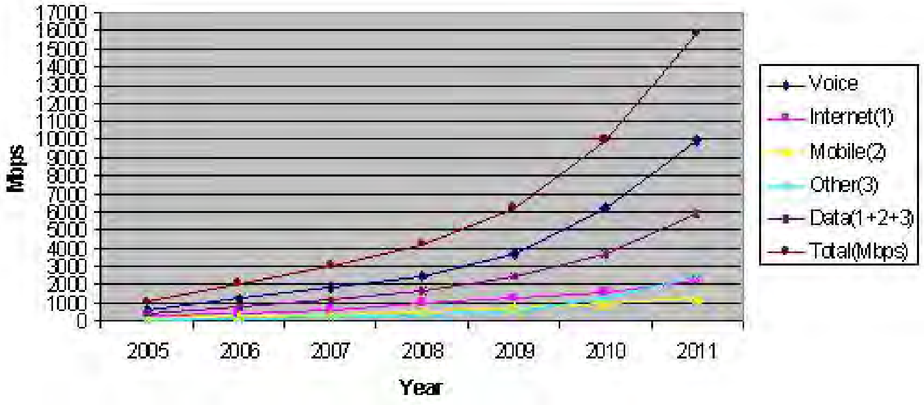


Fig. 3.8: Projected bandwidth capacity (2005-2011)

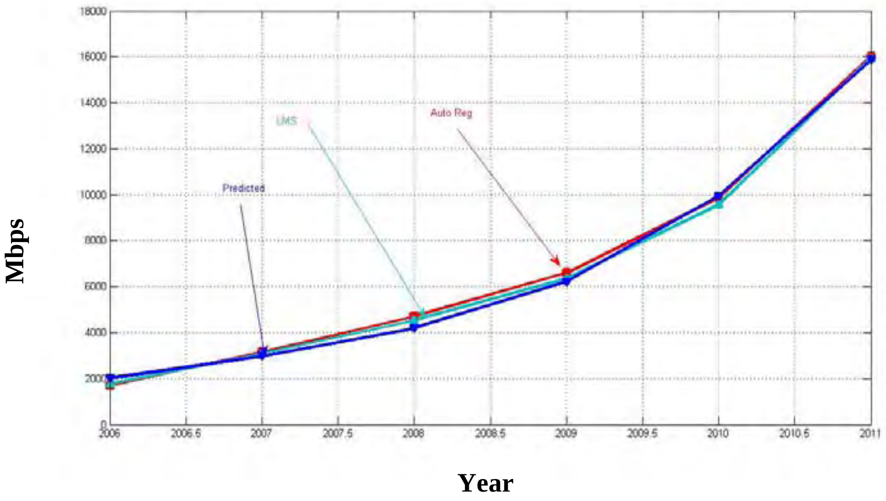


Fig. 3.9: Projected and formulated bandwidth capacity (2006-2011)

3.4 Comparison of the Developed Bandwidth Prediction Formula with that of the BTCL Projection

Depending on the current bandwidth demand, BTCL decides on the projected bandwidth, which is merely an estimate from the demand. However, we have collected, for the first time, relevant field data from the respective organizations to study the present and future capacity of the submarine cable, which will help assess the potential use of the available bandwidth. The comparative plots for the bandwidth for each individual service between the BTCL (2007-2011) and the prediction model is shown in Fig. 3.10. On the other hand, Fig. 3.11 shows a similar comparison in the total bandwidth demand.

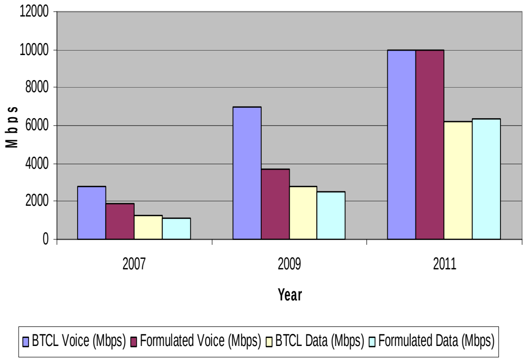


Fig. 3.10: Projected individual services bandwidth of BTCL and formulated (2007-2011)

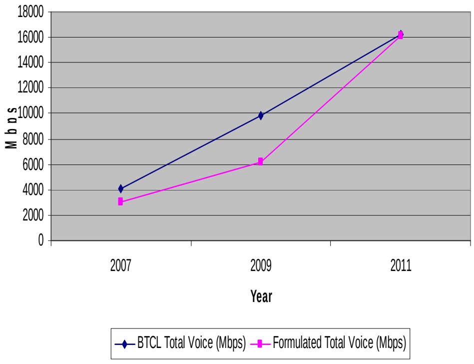


Fig. 3.11: Projected total bandwidth of BTCL and formulated (2007-2011)

From this Figures, it has been observed that in 2007 and 2011 projected bandwidth of BTCL and our formulated bandwidth are almost the same. In year 2009, the projected bandwidth of BTCL is higher than our formulated projected bandwidth. The bandwidth demand (W) will, of course, be influenced by some other factors, such as, tariff increase or decrease, income boost, cheaper network equipment, bigger Internet, more employment, and higher wages etc.

Therefore, the developed forecasting formula may be considered to predict the bandwidth demand of the submarine cable in Bangladesh fairly accurately. In future, the other factors may be included to increase the accuracy of prediction.

3.5 Summary

A lot of initiatives have been taken by both private and public sectors in the field of telecommunication and Information Communication Technology. There has also been a commendable advancement in developing the physical infrastructure while more are in the pipeline. Awareness of technology and the ability to use it and to build the infrastructure are key issues to the growth of ICTs in Bangladesh. BTCL along with private sectors have been taking care of the issues prevailing in the telecommunication, Internet and Data communications sector. However, to meet the growing need of bandwidth, appropriate measures have to be taken to tackle the issues in collaboration with all the parties involved, and thereby harness the maximum benefit of the submarine cable connectivity.

CHAPTER 4

DESIGN OF THE OPTICAL FIBRE BACKBONE NETWORK IN BANGLADESH AND ITS REDUNDANCY SCHEMES

Today’s world has seen an unprecedented development of Information and Communication Technology (ICT) which greatly facilitates the flow of information. ICT is now widely recognized as a critical tool to tackle development issues in the developing countries like Bangladesh. Access to information provides an opportunity to foster greater competitiveness, new economic growth and job creation, better access to basic services, improved health and education outcomes, and greater empowerment of rural communities [22-24]. In Bangladesh, digital switching systems already cover the big cities and sub-district towns. Most of the transmission networks implemented are digital. The backbone network is fully optical and connected to the outside world through SEA-ME-WE4 consortium. Thus, Bangladesh is apparently getting ready for various digital services. However given the current situation, the country is still way behind the expected level of achievement or future growth. The reason for this is that; though the core network is ‘digital’, some of the links between the telephone-office and the customer-office remain age-old ‘analog’ and some links are partially ‘digital’ after implementing the optical fiber connectivity throughout the country. Also all the districts in Bangladesh are yet to get coverage of the optical access network. Thus even though the basic infrastructure has been more or less constructed, appropriate link in the last mile is missing. It is worthy to note that most of the faults occur in this part (last mile network) of the network which is called *high speed connectivity access network.*

4.1 Types of Access Networks

Based on different transmission mechanisms, an access network can be divided into two categories; wired and wireless. A wired access network includes copper wire, optical fiber, and hybrid optical fiber/coaxial cable access network, etc. A wireless access network includes fixed and mobile networks. A copper wire access network can be divided into digital pair gain (DPG), high-bit-rate digital subscriber line (HDSL), asymmetrical digital subscriber line/loop (ADSL), etc. An optical fiber access network is divided into fiber-to-the-curb (FTTC), fiber-to-the-building (FTTB), and fiber-to-the-house (FTTH). A fixed wireless access network can be divided into microwave and satellite type, while a mobile access network is divided into wireless telephone, cellular mobile telephone, radio paging, satellite communication and trunk system, etc. In addition, there is wired or wireless integrated access network mode. Four types of access networks are available in Bangladesh:

i) x-DSL (ADSL) technology on existing copper wire
ii) Multi Service Access Network (MSAN) using optical fiber as primary network and Optical Network Unit (ONU) for broadband services
iii) Copper Cable Access Network
iv) Wi-MAX (Worldwide Interoperability for Microwave Access, Wireless broadband new technology)

In the following paragraphs, we will discuss each technology in brief and their availability in Bangladesh.

x-DSL technology: Digital Subscriber Line (DSL) technology is a modem technology that uses existing twisted-pair telephone lines to transport high-bandwidth data such as multimedia and video to give service to subscribers. The term x-DSL covers a number of similar yet competing forms of DSL technologies including ADSL, SDSL, HDSL, HDSL-2, G.HDSL, IDSL, and VDSL. x-DSL is drawing significant attention from implementers and service providers because it promises to deliver high-bandwidth data rates to wide spread locations with relatively small changes to the existing telecommunication infrastructure. x-DSL services are dedicated, point-to-point, public network access over twisted-pair copper wire on the local loop between a network service provider's central office and the customer site or on local loops created either intra-building or intra-campus. Currently most DSL deployments are ADSL, mainly delivered to residential customers.

Asymmetric Digital Subscriber Line (ADSL) provides simultaneous transport of asymmetric high capacity digital channels, together with Plain Old Telephone Service (POTS) on a single copper pair. It is only a point-to-point technology.

ADSL technology is asymmetric. It allows more bandwidth downstream—from a network service provider's central office to the customer site—than upstream from the subscriber to the central office. This asymmetry, combined with always-on access (which eliminates call setup) makes ADSL ideal for Internet/intranet surfing, video-on-demand, and remote LAN access. Users of these applications typically download much more information than they send. ADSL transports Voice Along With Video/Data although the voice and video/data operate independently. It can transmit 6 Mbps to the home and 640Kbps from the home over a distance up to 12,000 feet. It can also transmit 1.5 Mbps to the home and 64Kbps from the home over a distance up to 18,000 feet.

Availability in Bangladesh: Currently broadband connection [25] is available in most major cities like Dhaka and Chittagong. At present, more projects have been undertaken to extend it to all district towns.

Multi Service Access Network (MSAN): The strategy acknowledged by the developed countries concerning access network construction is to place optical fiber as near to users as possible. The optical access network is undoubtedly the keystone in the construction of a communication information network. Statistical analysis shows that the international optical fiber market for trunk network is basically steady, and the quantity of optical fiber used in the local network and access network is increasing. Thus, the application of optical fiber in access network represents a growing global trend. The available capacity (bandwidth) in SMW 4 submarine cable for Bangladesh is being used for three broad services: voice, data and Internet. At present bandwidth allocation for (data + Internet) and voice circuits are 1244 Mbps and 2799 Mbps respectively. It is also mentioned that around 800 Mbps is utilized in voice circuits in Dhaka division and other 5 divisions together utilize 280 Mbps whose owner is only Bangladesh Telecommunication Company Limited (BTCL). It is also observed that almost 50% bandwidth (1080 Mbps) is used of total allocation (2799 Mbps) in voice circuits.

Availability in Bangladesh: As of April 2008, 105 leased line Internet connections are in service. These connections (using Fast/Gigabit Ethernet) have been given from Gulshan (Dhaka), Moghbazar (Dhaka) and Nandan Kanon (Chittagong) PoPs (Point-of-Presence), Chiringa and Cox's-Bazar through optical fibers arranged by the customers. Among those, 87 connections are in Dhaka and 17 in Chittagong. It is notable that 5 corporate organizations and 6 universities now have optical connectivity. Internet connections are mostly limited to Dhaka, Chittagong, Sylhet, Khulna, and Bogra districts.

Copper Cable Access Network: Copper based outside plant of PSTN is probably seeing its last ages. It is losing the battle because; it cannot cater for modern digital services which the customers demand. Side by side, the modern access network gives better quality services to the customers and at the same time is easier and cheaper for the service provider to manage. The access network makes convergence of different services possible and appears user friendly. Properly designed, an access network can provide cable TV (CATV) connection facility, interconnection to ISP's in addition to usual services e.g., Voice and Data. It offers a flexible, easy last mile solution - speed 512 Kbps to 20 Mbps.

Availability in Bangladesh: Copper Cable connection is available in most major cities in Bangladesh to access CATV services.

Wi-MAX: The term wireless refers to telecommunication technology, in which radio waves, infrared waves and microwaves instead of cables or wires are used to carry a signal to connect communication devices. These devices include pagers, cell phones, portable PCs, computer networks, location devices, satellite systems and handheld digital assistants. Wireless technology is rapidly evolving and is playing an ever-increasing role in the lives of people throughout the world. Wireless technologies are differentiated by the following:

- Protocol - ATM or IP
- Connection type - Point-to-Point (P2P) or multipoint (P2MP) connections
- Spectrum - Licensed or unlicensed

Wireless technology enables users to physically move while using an appliance, such as a handheld PC, paging device, or phone. There is a wide-range of wireless devices that implement radio frequency (RF) to carry the communication signal. Some wireless systems operate at infrared frequencies, whose electromagnetic wavelengths are shorter than those of RF fields. Wireless systems can be divided into fixed, portable, and IR wireless systems. A Fixed wireless system uses radio frequencies requiring a line of sight for connection. Unlike cellular and other mobile wireless systems, they use fixed antennas with narrowly focused beams. Fixed wireless systems can be used for almost anything that a cable is used for, such as high-speed Internet connection and satellite television connection. Technology has brought higher radio frequencies with broader bandwidth that can carry more information and require smaller antennas, resulting in lower costs and easier to deploy systems. A Portable wireless system is a device or system usually battery-powered that is used outside the office, home or vehicle. Examples include handheld cellular phones, portable computers, paging devices and personal digital assistants (PDAs) which operate through microwaves and radio waves. An IR wireless system uses infrared radiation to send signals within a limited-range of communication. These systems are commonly used in television remote-control boxes, motion detectors and cordless computer keyboards and mice. With progressing new technologies IR wireless systems can now connect notebook computers and desktop computers used within the same local area network (LAN) workstation.

Signals with wavelengths greater than 1 GHz are known as microwave signals. These microwave signals can also be used as transmission medium. Digital microwave systems fall into two categories: wavelengths less than 10 GHz and wavelengths greater than 10 GHz. Bands that are below 10 GHz have long propagation distances (up to 30 miles). They are only mildly affected by climatic changes such as rain. Bands over 10 GHz, such as 24 GHz, LMDS (28 GHz), and 38 GHz, are very limited to distance (less than 5 miles). They are also quite susceptible to signal fades attributed to rain. Microwave systems can offer bandwidth in the range of 1-155 Mbps.

Availability in Bangladesh: Microwave, UHF and VHF radio links are the major transmission systems used in Bangladesh. All union headquarters (smallest administrative unit) are connected with their respective districts through radio links.

4.2 Utilization and Effect of Different Access Network

In Bangladesh, the access networks are still copper-based to support narrow-band services. This network is not capable of providing broad-band services. Therefore, it is urgently necessary to upgrade the copper-band OSP (Online Service Provider) by introducing modern access network at least in the metropolitan cities. Such access network will help contain ever-increasing number of switching centers in big cities, gather quality of service and lessen the cost of maintenance of the network. As a result, broad-band services like data, video, telemedicine, teleconferencing, e-commerce, CATV, etc. will get a boost [26]. Properly designed access network can solve interconnection of the ISPs and Telecom Operators to some extent.

In fact, connection to submarine cable [27] and introduction of modern access network may, in real terms, boost ICT in the country. To choose appropriate type of access network however, would need detailed study. The passive optical network based on ATM (Asynchronous Transfer Mode) technology may look prospective. Considering the developing trends of access network technology – active and passive, wired and wireless, broad-band and narrow-band etc.- the integration of these may have practical significance. Not only can it guide the construction of the access network, but can also ease the smooth transition from a narrow-band access network to an all-purpose broad-band access network.

The available access network for Bangladesh is being used for three broad services: voice, data and Internet. An extensive study is needed to study the existing network, to survey the potential of the submarine cable, and to evaluate the requirements of different ISPs, call centers, software companies, mobile and fixed phone operators etc. We have no specific plan based on the current demand and growth of the users of various telecommunications services. Therefore, extensive study is needed to forecast the future growth of the demand in various telecommunications services.

As part of the current study, a survey has been carried out on the access network utilization in Bangladesh. This survey considered the access networks that have been registered by different user groups like Internet Service Providers (ISPs), mobile operators, universities, fixed phone operators, banks, IPLCs and others.

4.3 Existing Problems and Proposed Solutions for Access Network in Bangladesh

4.3.1 The Challenges

There are several reasons behind the shortcomings of the existing access network in Bangladesh. The major reasons are:

(a) Lack of expertise or skilled personnel: In Bangladesh, non-technical or inexperienced personnel are working in ICT development sector. Hence, ICT sector is suffering in many crucial areas and most of the ICT infrastructures are difficult to implement or utilize to its full extent.

(b) Insufficient network infrastructure: Basic infrastructures like electricity, telephone, Internet connectivity are partially developed in Bangladesh. The country is yet to solve the electricity crisis for which many electronic devices cannot be used as they are needed for continuous service. It is expected that the electricity problem would be solved within next few years. Likewise, other infrastructures and basic services are also likely to be developed.

(c) High tariff: In urban areas, most of the educated people live, but all of them cannot afford to access the latest technology of the world. Computer, Mobile, Laptop etc. are still very expensive in Bangladesh. Also Internet connection fee is high as well.

As part of this study, from our survey, here we provide some crucial information about tariff and rental issues. For leased line Internet tariff of BTCL, price is available for almost all amount of bandwidth as the bandwidth is being delivered through Ethernet port.

Other regional operators do not have such flexibility what BTCL has. Table 4.1 clearly depicts the status of leased line Internet bandwidth charges of BTCL which seems to be attractive.

Table 4.1: Leased line Internet MRC in USD of some selected operators

Bandwidth (Duplex)	BTCL (Bangladesh)	VSNL (India)	PTCL (Pakistan)
2 Mbps	1752	3292	1500
45 Mbps	24964	34539	24000
155 Mbps	72651	94239	46500

From Table 4.1, it is observed that BTCL Leased Line Internet Monthly Rental Charge (MRC) is comparatively lower than other Asian operators; still not affordable for many in Bangladesh.

From the Tables 4.2 and 4.3 above, charges of different packages, especially, of VSAT and Submarine cable, show that the prices have not reduced extensively for Internet usage and other purposes, as had been expected before.

Table 4.2: Modem and rental charges

Speed	Modem Charge Lifetime (optional) one end	Yearly Rental charge for Modem (if supplied by BTCL)
64 Kbps and128 Kbps	USD 1200	USD 300
192 Kbps to 1024Kbps	USD 1800	USD 450
Above 1 Mbps	USD 3300	USD 825

Table 4.3: Rental charge for satellite half circuit

Annual Charge (1 yr. Commitment)	Monthly Charge (1 yr. Commitment)	Month to Month Charge
Tk. 680,000 (USD 9,715)	Tk. 56,667 (USD 810)	Tk. 68,000 (USD 971)
Tk. 578,000 (USD 8,257)	Tk. 48,167 (USD 688)	Tk. 57,800 (USD 826)
Tk. 510,000 (USD 7,286)	Tk. 42,500 (USD 607)	Tk. 51,000 (USD 729)

(d) Uneducated/Illiterate people: Uneducated/Illiterate people cannot use computer or digital based system. Most of the people are living in rural area of Bangladesh. And most of rural people are uneducated and do not know how to access digital system. Hence, even if the improvements in network infrastructure are done, a large portion of people would still be unable to get its benefit. Hence, only dealing with the enhancement of access network will not be a solution in the greater scale for its effectiveness.

(e) No specific master plan: Bangladesh already has an ICT policy, but the implementation of all clauses is yet to be done. The policy makers are also not conscious about the long term master plan. This particular issue poses a great challenge to implement any innovative solution or enhancement in this area.

4.4 Possible Network Design Solutions

Based on our findings and information gathered from the survey, a design plan has been offered [28-31] and the possible solutions are proposed for the access network in Bangladesh. In this section, we present our works with descriptions wherever necessary.

The network infrastructure may be built on the following two types of networks:

1. IP/MPLS (Multiprotocol Label Switching) Network
2. SDH (Synchronous Digital Hierarchy) Network

IP/MPLS Network: IP/Multiprotocol Label Switching (MPLS) is an emerging technology that aims to address many of the existing issues associated with packet forwarding in today’s internetworking environment. The MPLS architecture is designed to perform label switching that combines the benefits of packet forwarding based on Layer 2 switching with the benefits of Layer 3 routing. Similar to Layer 2 networks (for example, Frame Relay or ATM) MPLS assigns labels to packets for transport across packet or cell-based networks. The forwarding mechanism throughout the network is label swapping, in which units of data (for example, a packet or a cell) carry a short, fixed-length label that tells switching nodes along the packet’s path how to process and forward the data.

The significant difference between MPLS and traditional Ethernet technologies is the way labels are assigned and the capability to carry a stack of labels attached to a packet. The concept of a label stack enables new applications, such as Traffic Engineering, Virtual Private Networks, fast rerouting around link and node failures, and so on. Many applications of MPLS are Unicast routing, Multicast Routing, QoS, VPN and Traffic Engineering. Unicast routing, QoS and Traffic Engineering are used for a robust service provider network. Main advantages of MPLS are IP addressing flexibility, traffic isolation, configuration manageability, scalability and network design flexibility.

SDH Network:

SDH (Synchronous Digital Hierarchy) is an international standard for high speed telecommunication over optical/electrical networks which can transport digital signals in variable capacities. It is a synchronous system which intends to provide a more flexible, yet simple network infrastructure. SDH (and its American variant-SONET) emerged from standard bodies somewhere around 1990. These two standards create a revolution in the communication networks based on optical fibers, in their cost and performance. We use SDH network plan for the following reasons:

- When networks need to increase capacity, SDH simply acts as a means of increasing transmission capacity.
- When networks need to improve flexibility, to provide services quickly or to respond to new change more rapidly.
- When networks need to improve survivability for important user services.
- When networks need to reduce operation costs, which are becoming a heavy burden.

SDH Protection - Two kinds of protection schemes could be there for SDH networks. We discuss both of them in the following paragraphs.

(a) Linear Protection (1+1):

a. In this topology (1+1 protection), each provider (For example, Fig. 4.1 shows only two providers which are sharing their resources with each other and each provider is managing three different locations), for each of the working unit/path (which can be either underground/overhead or both underground or both overhead) there will be a corresponding protection unit.

b. Both the units will be carrying data all the time; the receiving end will select the better of the two signals.

c. In case of failure, there will be a switching from ‘working’ to ‘protection’.

d. Even if the fault in the working unit is rectified, there will be no automatic switching from protection unit back to working unit.

e. This is called Non-Recursive type; because there is no automatic reversion from working to protection even when the working unit is functioning properly.

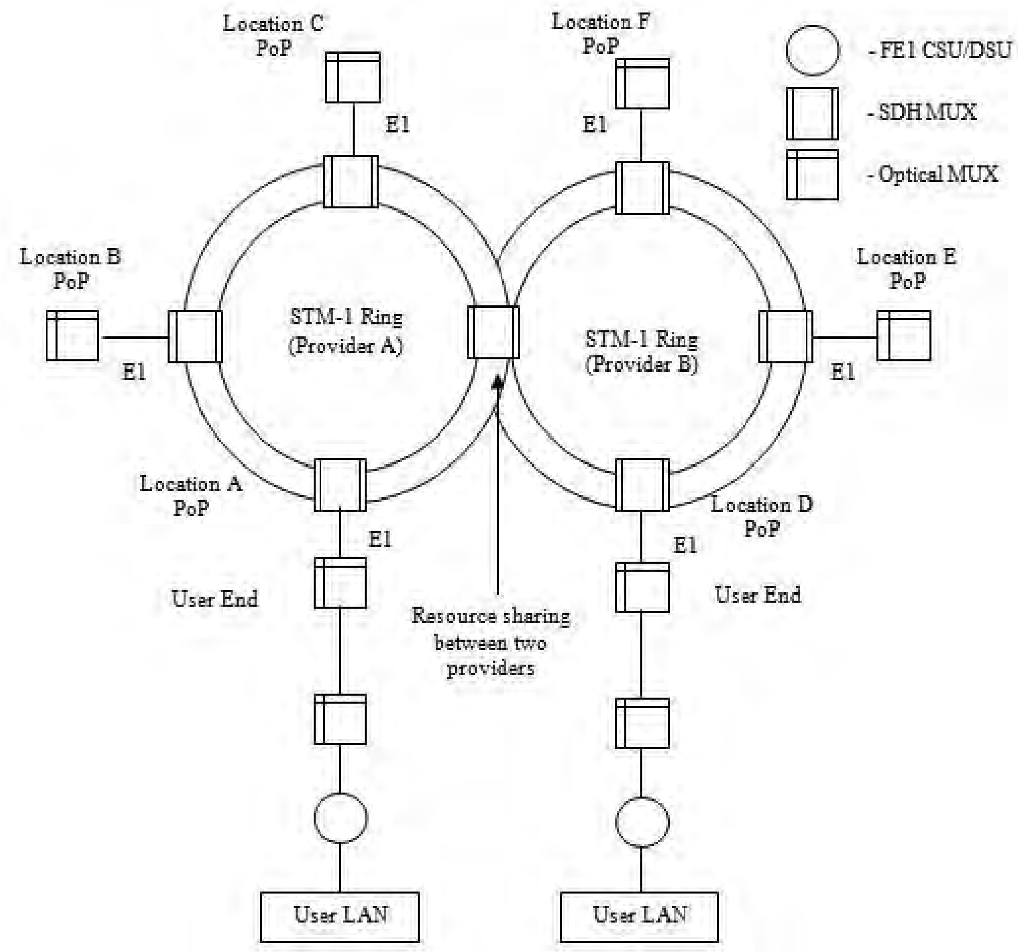
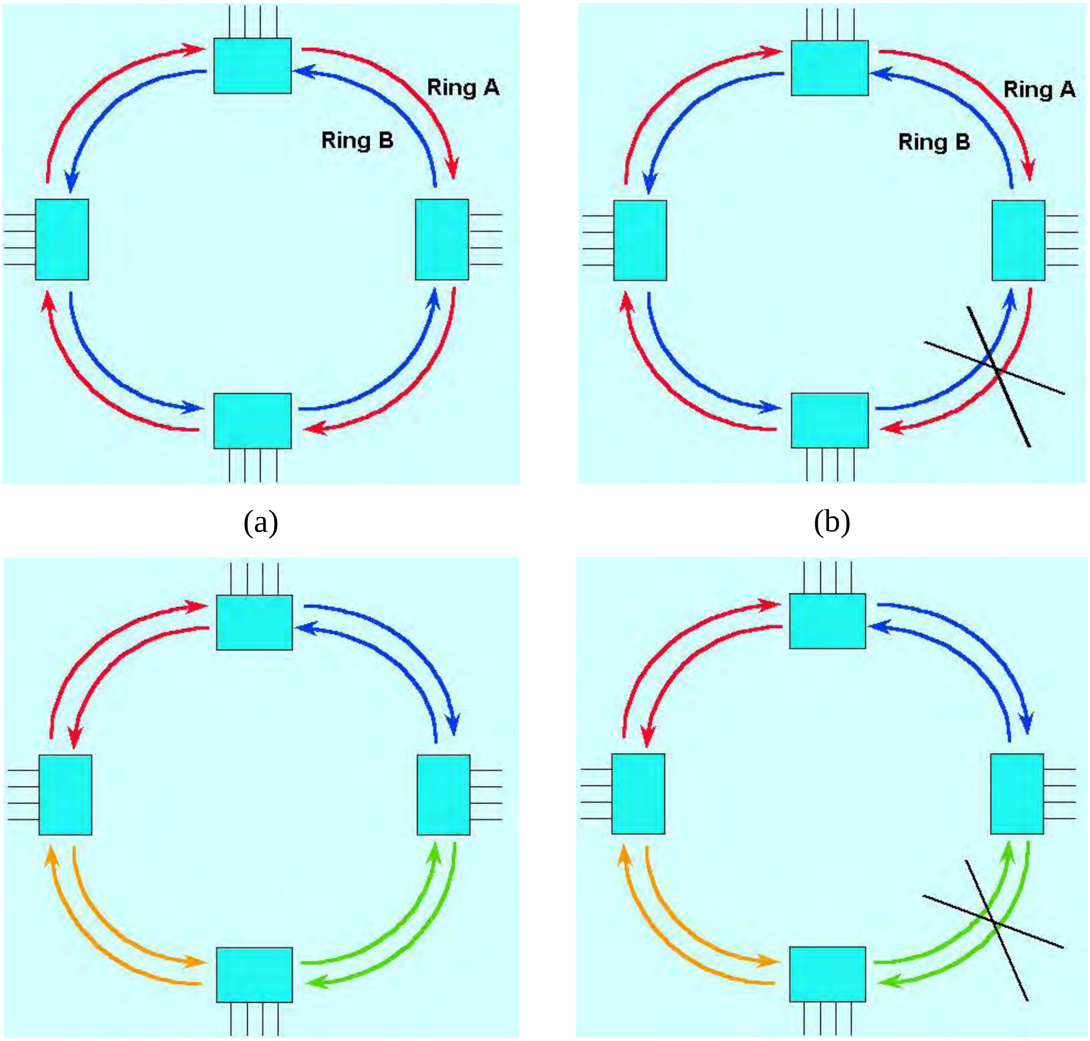


Fig. 4.1 : Different Providers and Different Locations, SDH Network for any city (Physical Topology)

The SDH gives the ability to create topologies with protection for the data transferred. Following are some examples for protected ring topologies (Fig. 4.2 [(a), (b), (c), (d)]).

In Fig. 4.2(a), we can see Dual Unidirectional Ring. The normal data flow is according to ring A. Ring B carries unprotected data which is lost in case of breakdown or it carries no data at all. In case of breakdown, rings A & B become one ring without the broken segment.



(a) (b)

(c) (d)

Fig. 4.2: Different Cases of Ring Topologies

The Bi-directional Ring (Fig. 4.2(c)) allows data flow in both directions. For example, if data from one of the sites has to reach a site which is next to the left of the origin site, it will flow to the left instead of doing a whole cycle to the right. In case of breakdown, some of the data are lost and the important data are switched. For example, if data from a site should flow to its destination through the broken segment, it will be switched to the other side instead.

In this topology, we can minimize the resource duplication and it is highly protective network design. Fig. 4.3 displays the design where only two providers are sharing their resources with each other and each provider is maintaining same three locations but different routes (which may be either underground/overhead or both underground or both overhead).

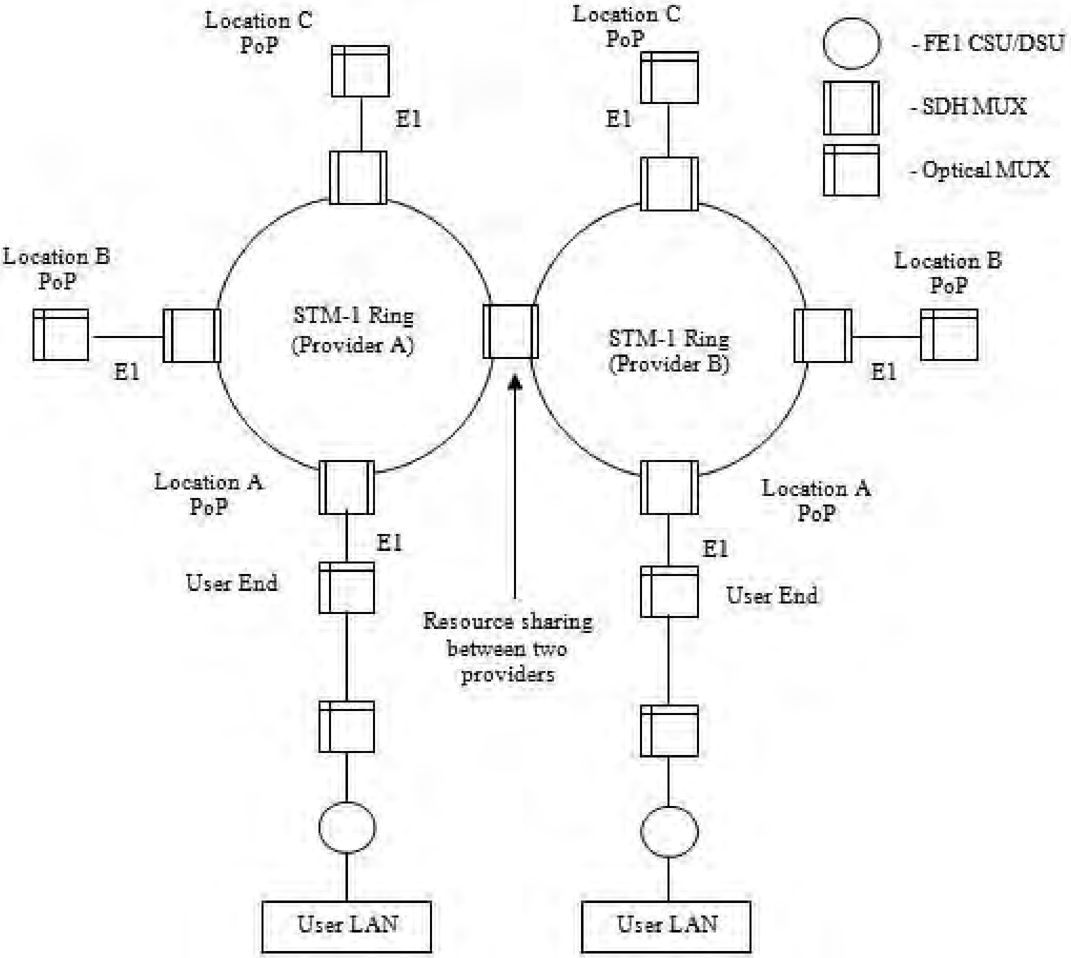


Fig. 4.3: Different Provider, Same Locations but Different Path

One of the services may be the working unit and other will be a corresponding protection unit. Both the units will be carrying data all the time; the receiving end will select the better of the two signals. In case of failure, there will be a switching from working to protection. Overall, here, we can minimize the resource duplication and costs as well.

(b) Ring Protection:

1. In unidirectional rings, signal is being carried in only one direction that is either clockwise or anti-clockwise.
2. Only in case of failure, there will be a switching in the other direction.
3. A simpler method is to use the so-called path switched ring.
4. Traffic simultaneously over the working line and the protection line.
5. If there is an interruption, the receiver switches to the protection line and immediately takes up the connection.

Fig. 4.4 shows the physical topology of the six major divisions in Bangladesh (A new division, 'Rangpur' is not included here as still now it is considered under 'Rajshahi' division). In this physical topology, we recommend that Dhaka Division will have the central office which is connected with all the other five divisions through optical fiber as well as radio link and that five divisions will be connected by ring topology in the same way.

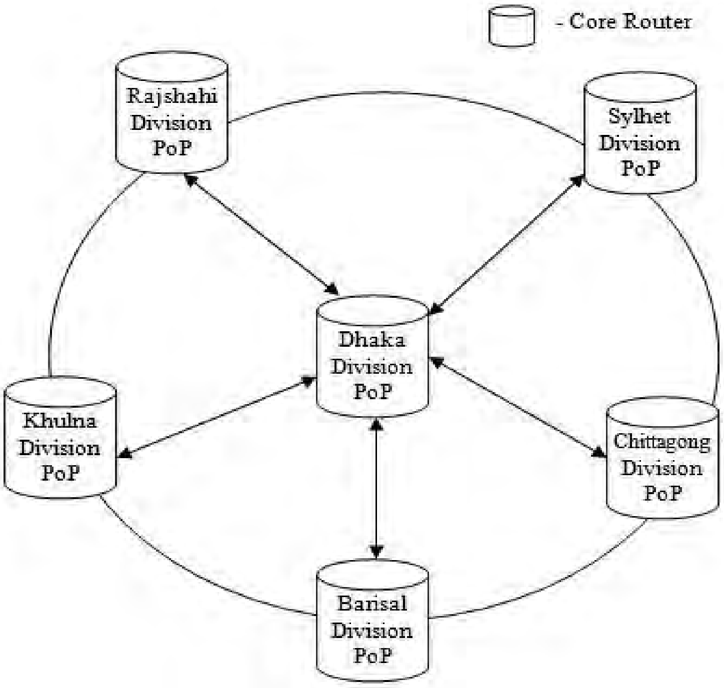


Fig. 4.4: Physical Topology of Six Divisions in Bangladesh

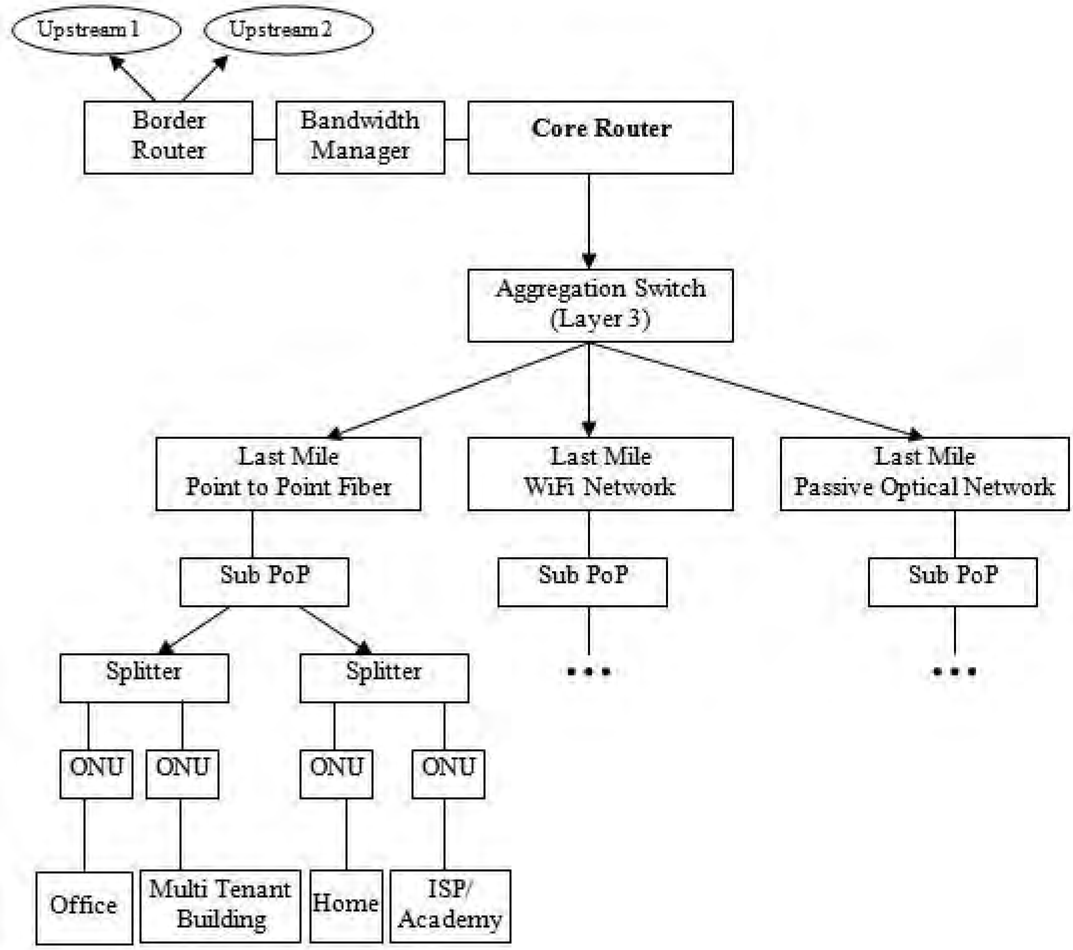


Fig. 4.5: Last Mile Solution of Optical Fiber Network for Each Division in Bangladesh

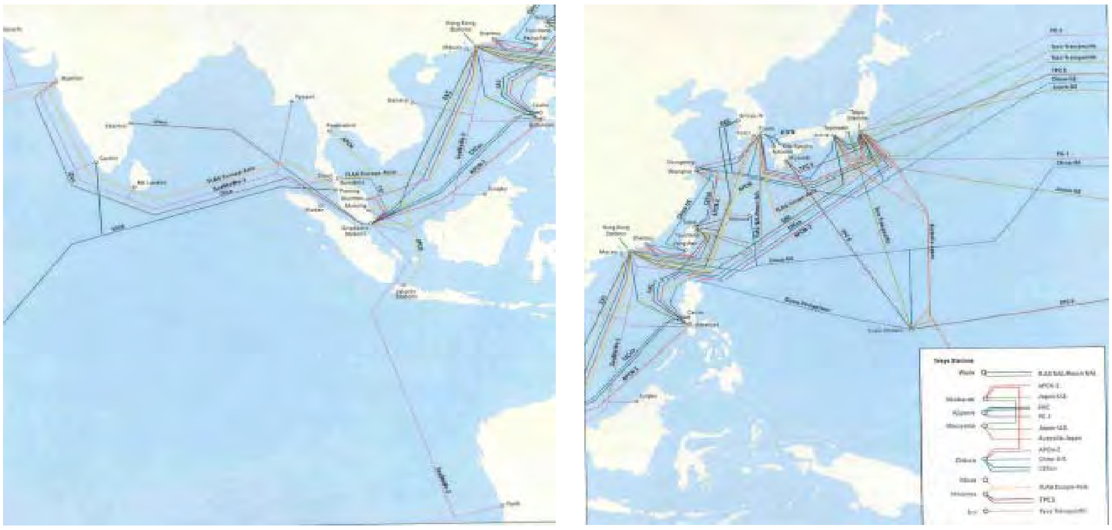
So, in case of failure, there will be a switching from any divisional PoP (Point of Presence) which will act as protective unit. We also recommend that network infrastructure of each division can be implemented by two to three providers that will minimize the resource duplication and costs. Fig. 4.5 shows the last mile solution of optical fiber network for each division in Bangladesh.

4.6 Redundancy Schemes for National and International backbone networks in optical transmission system with appropriate topologies

Redundant high speed connectivity access network can defend in case of cable failure or cut off and offer the best service, and ensure the data traffics for successful transfer of data packets. If we minimize the resource like cable, major system equipments, network setup, manpower etc. duplication in this case, cost reduction becomes attractive. In fact, the importance of redundant high speed connectivity access network for communication of a country is manifold. Bangladesh can take advantage of the redundant high speed connectivity access network under the following unexpected circumstances:

a. To Protect cable failure or cut off;
b. To achieve zero downtime service;
c. To enable new applications, such as traffic engineering, Virtual Private Networks (VPNs), fast re-routing around link and node failures, and so on.

Major submarine cable systems of South Asia and East Asia are shown in Fig. 4.6 (a) and 4.6(b). And international redundant scheme is shown in Fig. 4.7.



(a) (b)

4.6 : Major submarine cable system in (a) South Asia and in (b) East Asia.

Currently Bangladesh is connected from SMW-4 in Cox's Bazar. If it is cut off whole Bangladesh will be disconnected from the international communication. We need another connection from SMW-3 in Teknaf or SMW-5 in Mongla. SMW-3 covers Japan to Western Europe via Singapur, India, Middle East and Mediterranean countries. And SMW-5 covers Europe, Africa and Asia countries.

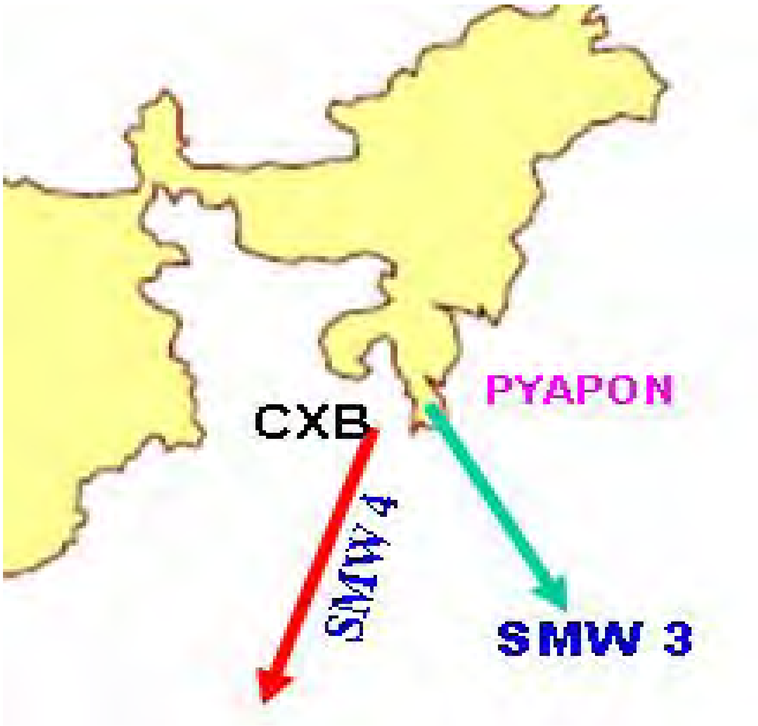


Fig. 4.7 : International redundant scheme

To harness the benefit of redundant high speed connectivity access network, we present our proposed design in this paper with the goal of achieving zero downtime. We also suggest such a backbone and a multi-core fiber cable network that constitutes of various loops and branches providing redundancy in data path. This means that in case of most cable failure or cut off, it should be re-routing the data traffic to ensure that the data packets reach their intended recipients. Our designs ensure minimization of resource duplication as well as costs for implementation. Finally, redundant path or route could be created to protect the network and for providing the best possible service.

The major inter-city backbone network of Bangladesh and the proposed redundancy schemes are shown in Fig. 4.8.

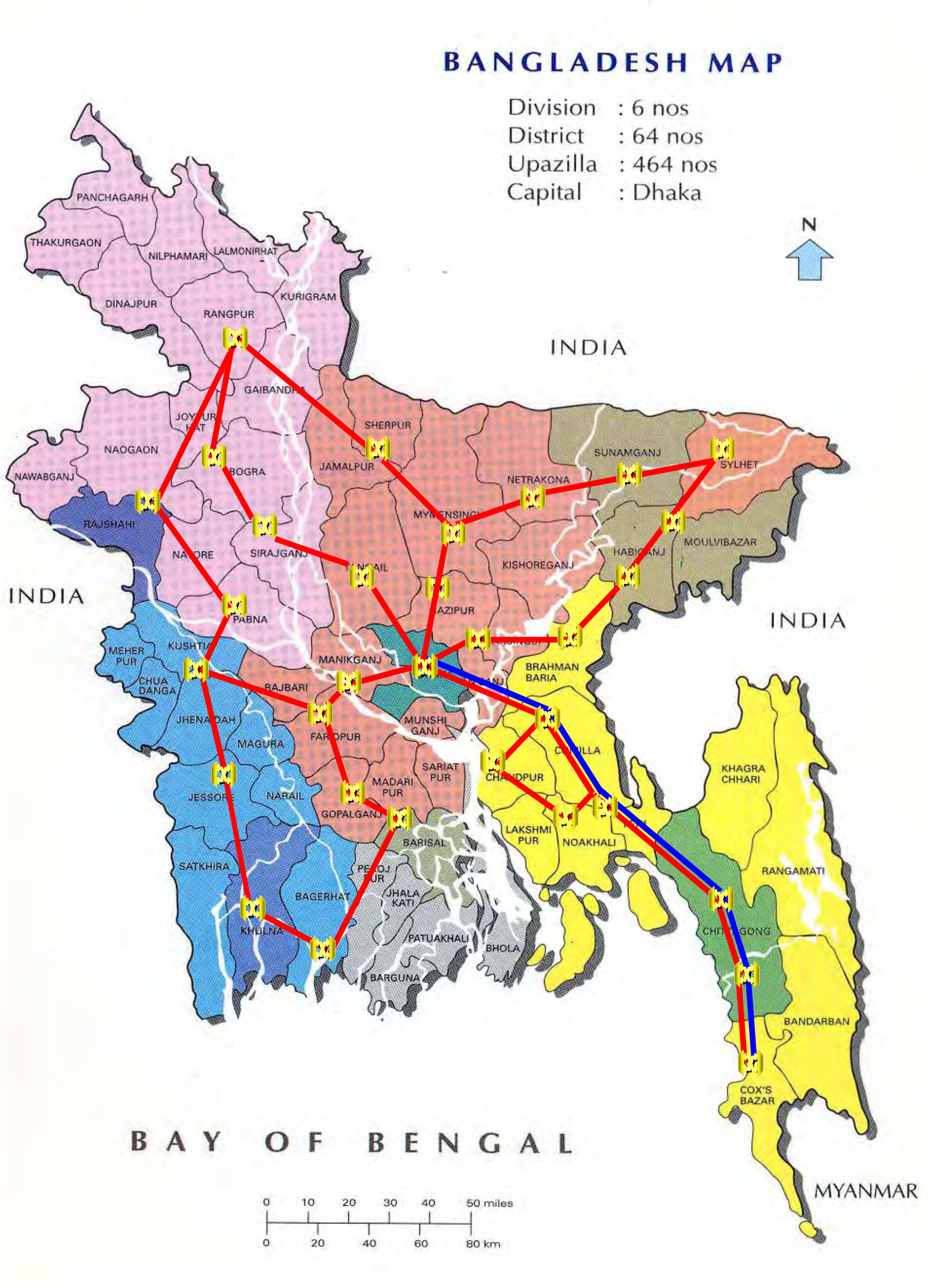


Fig. 4.8: Major Intercity backbone network and it’s redundant scheme

The block diagrams of the major inter-city backbone network of Bangladesh are shown in Fig. 4.9 to fig. 4.12.

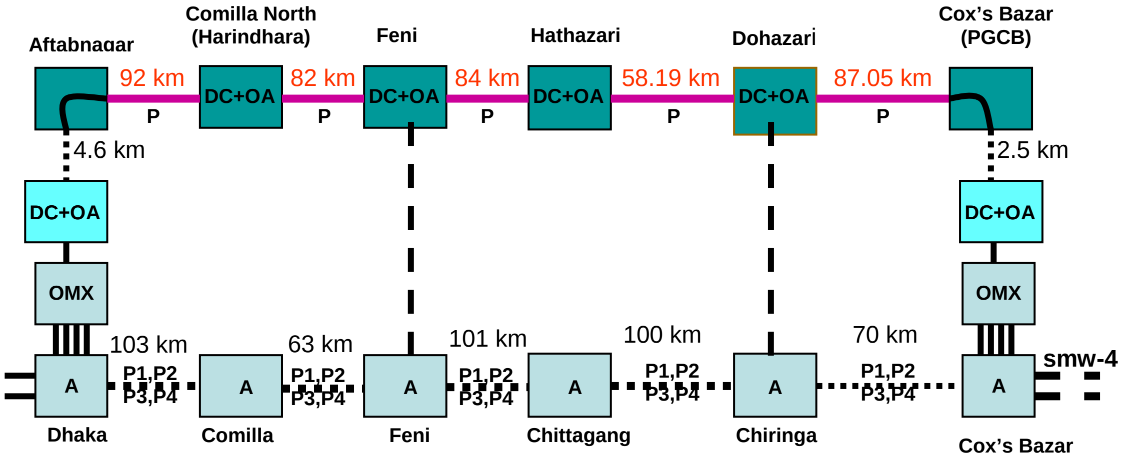


Fig. 4.9: Block diagram of Dhaka to Cox's Bazar Backbone Network

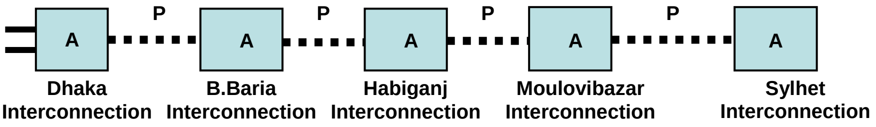


Fig. 4.10: Block diagram of Dhaka to Sylhet Backbone Network

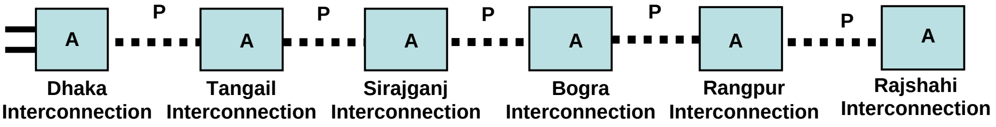


Fig. 4.11: Block diagram of Dhaka to Rajshahi Backbone Network

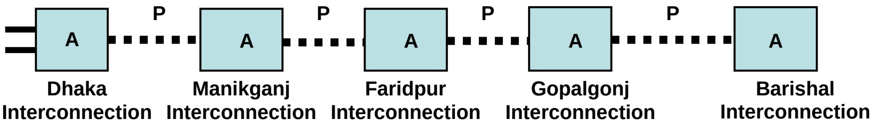


Fig. 4.1 2: Block diagram of Dhaka to Barishal Backbone Network

An optimum backbone network plan has been proposed for the following major inter-city routes of Bangladesh:

(i) Dhaka – Comilla – Feni - Chittagong – Chiringa - Cox’sBazar;
(ii) Comilla – Chandpur – Noakhali – Feni;
(iii) Dhaka – Gazipur - Mymensingh – Netrokona – Sunamgonj – Sylhet;
(iv) Mymensingh – Sherpur – Rangpur;
(v) Dhaka - Tangail – Sirajgonj – Bogra – Rangpur;
(vi) Rangpur - Rajshahi – Pabna – Khustia – Jessore – Khulna - Mongla - Barishal;
(vii) Faridpur – Khustia;
(viii) Dhaka – Narshidi - Brahmonbaria – Habigonj – Moulovibazar – Sylhet and
(ix) Dhaka – Manikgonj – Faridpur – Gopalgonj – Barishal.

4.6 Summary

It has been strongly felt that a fiber optic network redundancy with a goal of achieving zero downtime and making a backbone consisting of a multi-core fiber cable network with various loops and branches, may provide redundancy in the data path. This means that in case of any unwanted cable failure, data traffic could be re-routed so that they would reach their intended recipients without failure. Therefore a better optical fiber infrastructure is the key requirement of availing the full potential of the submarine cable capacity.

In Bangladesh, many private operators have implemented optical fiber network individually in the same location and following the same style (laid underground or drawn overhead). They also have radio links. For this reason, resources are duplicated and investment became very huge. As these are not well-planned and sporadic efforts, there are no routes to provide quality services for end users. It is therefore, necessary that the network should be implemented by sharing all the available resources. Such a design would be to avoid resource duplication and cost minimization, and redundant routes have to be established at all possible levels to ensure quality and reliable service to the end users.

CHAPTER 5

SIMULATION RESULTS AND DISCUSSION

The steps and procedures for designing an optical fiber backbone network in Bangladesh has been described in chapter 4. The design had been proposed for the following major inter-city links.

(i) Dhaka – Comilla – Feni - Chittagong – Chiringa - Cox'sBazar;
(ii) Comilla – Chandpur – Noakhali – Feni;
(iii) Dhaka – Gazipur - Mymensingh – Netrokona – Sunamgonj – Sylhet;
(iv) Mymensingh – Sherpur – Rangpur;
(v) Dhaka - Tangail – Sirajgonj – Bogra – Rangpur;
(vi) Rangpur - Rajshahi – Pabna – Khustia – Jessore – Khulna - Mongla - Barishal;
(vii) Faridpur – Khustia;
(viii) Dhaka – Narshidi - Brahmonbaria – Habigonj – Moulovibazar – Sylhet and
(ix) Dhaka – Manikgonj – Faridpur – Gopalgonj – Barishal.

Owing to the intensive involving tasks to be undertaken and also for the time constraints, simulations have been performed only on the complex link between Dhaka and Cox's Bazar (i.e. Dhaka-Comilla-Feni-Chittagong-Chiringa-Cox's Bazaar). This link connects the access network to the SEA-ME-WE-4 landing station (Cox's Bazar). The major findings of the simulation results are presented and discussed in this chapter. The Quality of Service (QoS) parameters, such as, BER performance, Q-Value, NF, Receiver Sensitivities and penalties are also calculated at the relevant receiver side under the direct detection schemes. The theoretical approach to Q-factor and BER has been included in Appendix-B.

5.1 Choice of Design Parameters

In order to determine the effect of chromatic dispersion and amplifier noise, the Q-factor and Bit Error Rate (BER) performance have been developed as a function of average signal count per bit, considering the effect of shot noise, thermal noise, spontaneous emission noise and laser phase noise. The nominal values of the parameters which are used throughout the calculation are included in Table 5.1.

Table 5.1: Common Parameters of the Optical Communication link

Data source

Parameter Name	Value
Bit Rate	10 Gbps
Samples per bit	13
Sequence	Random

NRZ Modulator

Parameter Name	Value
Lower Level	-2.5
Upper Level	2.5
Crossing point	50%

LASER

Parameter Name	Value
Center emission wavelength	1550 nm
Source status	1
CW power	3 dBm or 1.58 mW
FWHM linewidth	10 MHz

Amplitude Modulator

Parameter Name	Value
Excess loss	3 dB
Maximum transmissivity offset voltage	5 V
-3 dB bandwidth	10 GHz

Fiber

Parameter Name	Value
Fiber loss	0.2 dB/Km
Fiber dispersion	16 ps/nm/km
Non- linear refractive index	2.5E-20
Core effective area	80.0 10^(-12)m^2
Fiber non linearity co-efficient	1.26677 1/W/Km
Fiber Average beat length	5.0 m
Fiber PMD	0.12 ps/km^0.5

Booster

Parameter Name	Value
Doped Fiber length	19.0 m
Input insertion loss	1.2 dB
Output insertion loss	0.8 dB
Power	17.0 dBm or 50.11 mW

Amplifier

Parameter Name	Value
Output Power	17 dBm or 50.11 mW
Maximum Small-signal Gain	15 dB

Dispersion Compensator Fiber (DCF)

Parameter Name	Value
Fiber length	24 Km
Fiber loss	0.6 dB/Km
Fiber dispersion	-80 ps/nm-km

Optical filter

Parameter Name	Value
Notch filter	Bandpass
Number of poles	1
Center wavelength	1550 nm
-3dB two-sided bandwidth	52 GHz

Receiver Sensitivity

Parameter Name	Value
Photodiode type	PIN or APD
Bit Rate	10 Gbps
Quantum efficiency	0.75
Overall receiver responsivity	1.0 A/W
Sensitivity (pin)	-27 dBm

Electrical filter

Parameter Name	Value
Type	Lowpass
Number of poles	1
-3dB Bandwidth	10 GHz

First of all, the Q-factor and BER performance have been calculated without considering dispersion compensation for different values of chromatic dispersion, Noise Figure (NF), APD gain, wavelength and optical bandwidth as a parameter and the results are also plotted.

Next, the DCF (Dispersion Compensator Fiber) and EDFA is considered and the Q-factor and BER performance are evaluated again. Then the correlation diagram, BER performance at optimum threshold with an equivalent Q for the optimum decision are presented and evaluated.

Finally, the DCF (Dispersion Compensator Fiber) and SOA is considered and the Q-factor and BER performance are also evaluated. From the family of performance curves, the receiver sensitivity has been calculated for a bit error rate of 10^{-6}.

The equipment performance penalties and link power margin parameters that are assumed for the system are shown below in Table 5.2.

Table 5.2: Equipment performance penalties and Link power margin parameters of the Optical Communication link

Equipment performance penalties	**Desired Value**
Dispersion penalty	<= 0.5dB
Source penalty	<= 0.5dB
Temperature dependence	<= 0.5dB
Allowance for aging	<= 0.5dB
Connector loss	<= 2.0dB
Total penalties	**>= 4.0 dB**
Link power margin	**>= 5 dB**

The optical amplifier parameters that are used for the system are shown in Table 5.3.

Table 5.3: Optical Amplifier Parameters of the Optical Communication link

Specification	**Desired Value**
Gain	14 – 20 dB
Noise Figure	≤ 7 dB
Maximum Output Power	≥ 17 dBm
Wavelength	1530.139 nm to 1565.29 nm

Table 5.4 shows the optical multiplexer parameters that are used for the system.

Table 5.4: Optical Multiplexer Parameters of the Optical Communication link

Specification	**Desired Value**
Maximum Total Input Power	≥ 17 dBm
Minimum Return Loss	≥ 40 dB
Passband	Centre Wavelength ± 0.25 nm
Minimum band isolation – drop	35 dB
Minimum band isolation – thru out	20 dB
Insertion Loss (port to port) – add path	3.0 dB (maximum) 2.2 dB (typical)
Insertion Loss (port to port) – drop path	3.2 dB (maximum) 2.5 dB (typical)
Insertion Loss (port to port) – pass-through per band	1.2 dB (maximum) 0.8 dB (typical)

Table 5.5 includes the Gigabyte Ethernet (GE) interface parameters that are used for the system.

Table 5.5: Gigabyte Ethernet (GE) Interface parameters of the Optical Communication link

Sl. No	**Properties**	**Unit**	**Value**
1	Target Distance	kilometer	10
Transmitter parameter			
2	Operating Wavelength	nm	1270 to 1355
3	Maximum mean launched power	dBm	-3 ± 0.5
4	Minimum mean launched power	dBm	-2
5	Minimum extinction ratio	dB	9
6	Eye Pattern mask	IEEE802.3z-compliant	
Receiver parameter			
7	Receiver type		PIN
8	Operating Wavelength	nm	1270 to 1355
9	Receiver Sensitivity	dBm	-18
10	Minimum receiver overload	dBm	-3

5.2 Safety Requirements for the Link Design

It has been assumed that the following optical safety requirements are met:

1. Generally if the section is interrupted (e.g. if a fiber breaks), then measures shall be implemented to ensure that no risk is caused by LASER light escaping uninterruptedly.
2. In the event of an optical signal failure at the incoming port with a duration $\leq$ 500 ms, and certainly within 600 ms, the LASER in the opposite direction is switched off by the receiver within 0.85 seconds, and the affected segment will thus be shut down. It shall not be possible to activate the forced facility during error-free operation.
3. The attenuation coefficient of the fiber, measured in the cable delivery length, shall not exceed 0.36 dB/km for 1300 nm wavelength and 0.22 dB/km at 1550 nm wave length. Graphs showing temperature dependence of attenuation characteristics shall be presented by the manufacturer in the range between 0^oC to 60^oC. The maximum attenuation variation in the temperature range should be 0.01 dB/km.

4. The chromatic dispersion in the cable delivery length shall be less than 3.5 ps/nm-km in the interval 1285-1330 nm and less than 18 ps/nm-km at 1550 nm.

5. Optical Fiber cable should operate normally under the following environmental conditions:-

   a. Operating temperature – 5^0C to 60^0C
   b. Operating relative humidity _ 60^0C to 100^0C
   c. Storage temperature - -40^0C to 70^0C
   d. Storage relative humidity - 60^0C to 95^0C

6. The following SDH levels shall be available in the offered SDH transmission equipment:

   a. STM-1 at 155,520 Kbps.
   b. STM-4 at 622,080 Kbps
   c. STM-16 at 2448,320 Kbps. and/or
   d. STM-64 at 10 Gbps

7. The amplifier shall be used for optical booster (i.e. erbium doped optical amplifier) or pass through ADM instead of the Regenerator in a cost-effective solution.

8. The ADM equipment shall terminate and originate both the Multiplexer Section Overhead (MSOH) and Regenerator Section Overhead (RSOH).

5.3 Total Loss Calculations

Table 5.6 shows the total loss in fiber and ODF for the existing link using the BTCL fiber (4 links). The Guaranteed Link Margin is considered to be ≥ 5 dB is considered for the system.

Note: *Guaranteed Link Margin = (Nominal Receive Level – Receiver Sensitivity).*

Table 5.6: Total loss for the link using BTCL fiber, 4 Links (P1, P2, P3 and P4)

Link	Distance (km)	Total Loss in fiber and ODF
Moghbazar- Comilla	103	23 dB
Comilla-Feni(BTCL)	63	19 dB
Feni(BTCL) – Chittagang	101	23 dB
Chittagang – Chiringa	100	23 dB
Chiringa-Cox’s Bazar	70	17 dB
Comilla- Moghbazar	103	23 dB
Feni(BTCL)- Comilla	63	19 dB
Chittagang- Feni(BTCL)	101	23 dB
Chiringa – Chittagang	100	23 dB
Cox’s Bazar – Chiringa	70	17 dB

Table 5.7 shows the total loss in fiber and ODF for the redundant route using the PGCB fiber (single link).

Table 5.7: For the link Using PGCB fiber, Single link

Link Name	Distance (km)	Total Loss in fiber and ODF
Moghbazar- Harindhara (Comilla North)	103.8	26 dB
Harindhara (Comilla North)- Feni (PGCB)	82	22 dB
Feni(PGCB)- Hathazari	84	24 dB
Hathazari-Dohazari	58.19	26 dB
Dohazari-Jhilonza (Cox’s Bazar)	89.55	26 dB
Harindhara (Comilla North)-Moghbazar	103.8	26 dB
Feni(PGCB)-Harindhara (Comilla North)	82	22 dB
Hathazari-Feni (PGCB)	84	26 dB
Dohazari-Hathazari	58.19	24 dB
Jhilonza (Cox’s Bazar)- Dohazari	103.8	26 dB

5.4 Simulation Results

The simulation analysis has been performed using the famous OptSim simulator. The following three cases have been considered for the simulation, and considering the various links between the route from Dhaka to Cox’s Bazar:

(1) Only using EDFA (Erbium Doped Fiber Amplifier)

(2) Using DCF (Dispersion Compensator Fiber) and EDFA

(3) Using DCF and SOA (Semiconductor Optical Amplifier).

The corresponding simulation results for the three cases have been discussed in sections 5.4.1, 5.4.2 and 5.4.3, respectively.

5.4.1 Block Diagram and Simulation Results of the 10 Gbps Single-Channel Single-Fiber Dhaka–Comilla–Feni–Chittagong–Chiringa–Cox's Bazar transmission link (437 km long) using EDFA alone

The block diagram of the 10 Gbps transmission link connecting Dhaka to Cox's Bazar landing station is shown in Fig. 5.1.

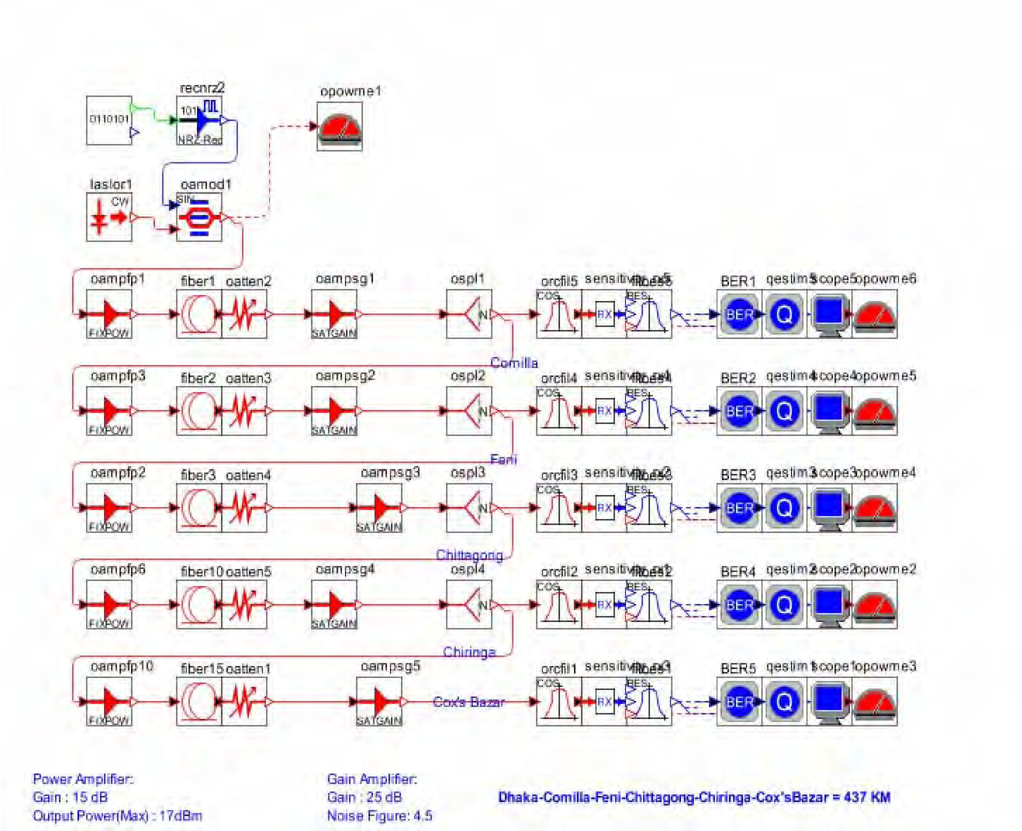


Fig. 5.1: Block diagram of the 10 Gbps transmission link using EDFA alone.

The design assumes that only EDFA (Erbium Doped Fiber Amplifier) has been used. The correlation diagram between BER Vs NF and Q-Value Vs NF for the link under current study are shown in Figures 5.2 to 5.11 (the corresponding data are included in Appendix-C (Table C.1 and C.2).

Fig. 5.2 shows the BER Vs NF for the link of Dhaka-Comilla.

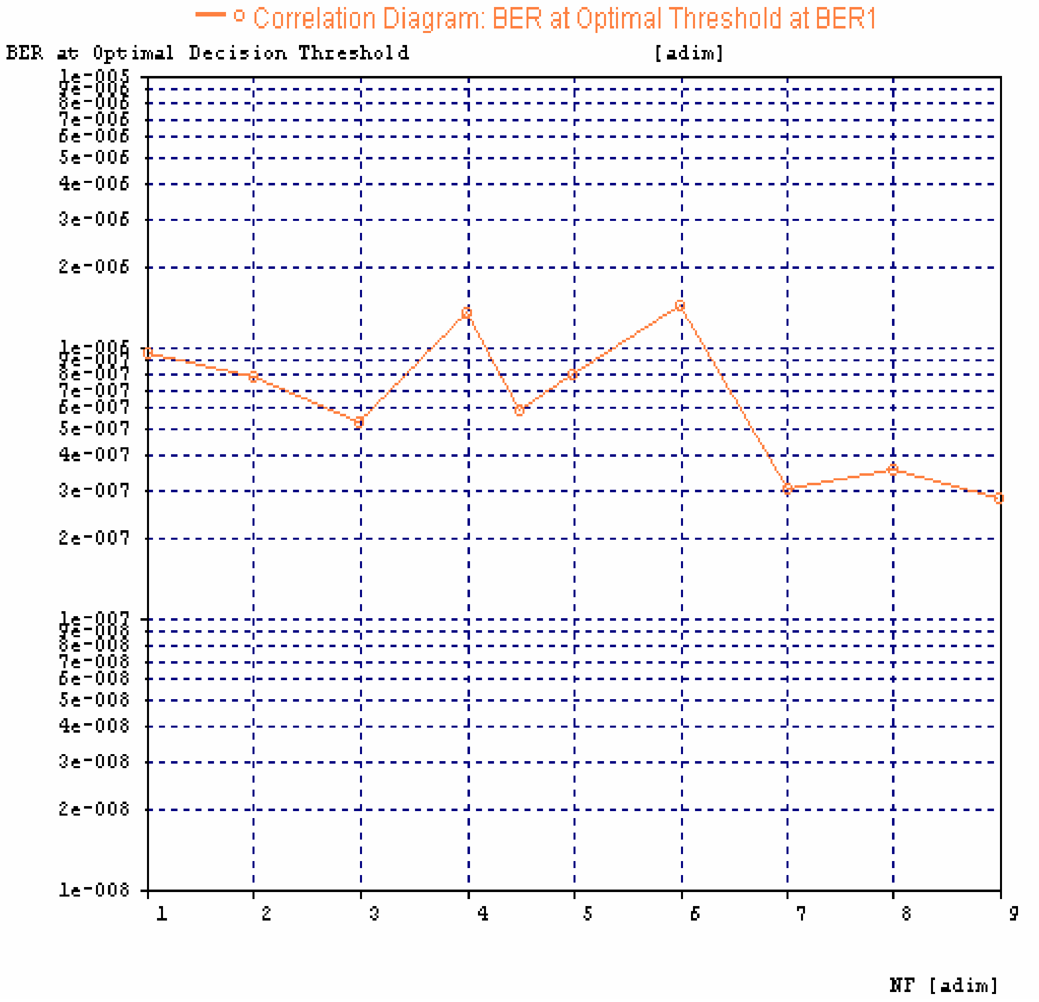


Fig. 5.2: BER Vs NF for the link of Dhaka – Comilla

For the combination of LASER-NRZ-EDFA-SM-APD, BER Vs. NF has been calculated for a distance of 103 km (Dhaka to Comilla). It has been observed that within a NF range of 3 to 7 dB, the BER lies within the **acceptable limit of 10^{-6}** (under this case BER is even better ie. 10^{-7}, which is much less than the acceptable value). Owing to the presence of noise and jitter, the BER performance curve is seen to have ripples.

Fig. 5.3 shows the Q-Value Vs NF for the link of Dhaka-Comilla.

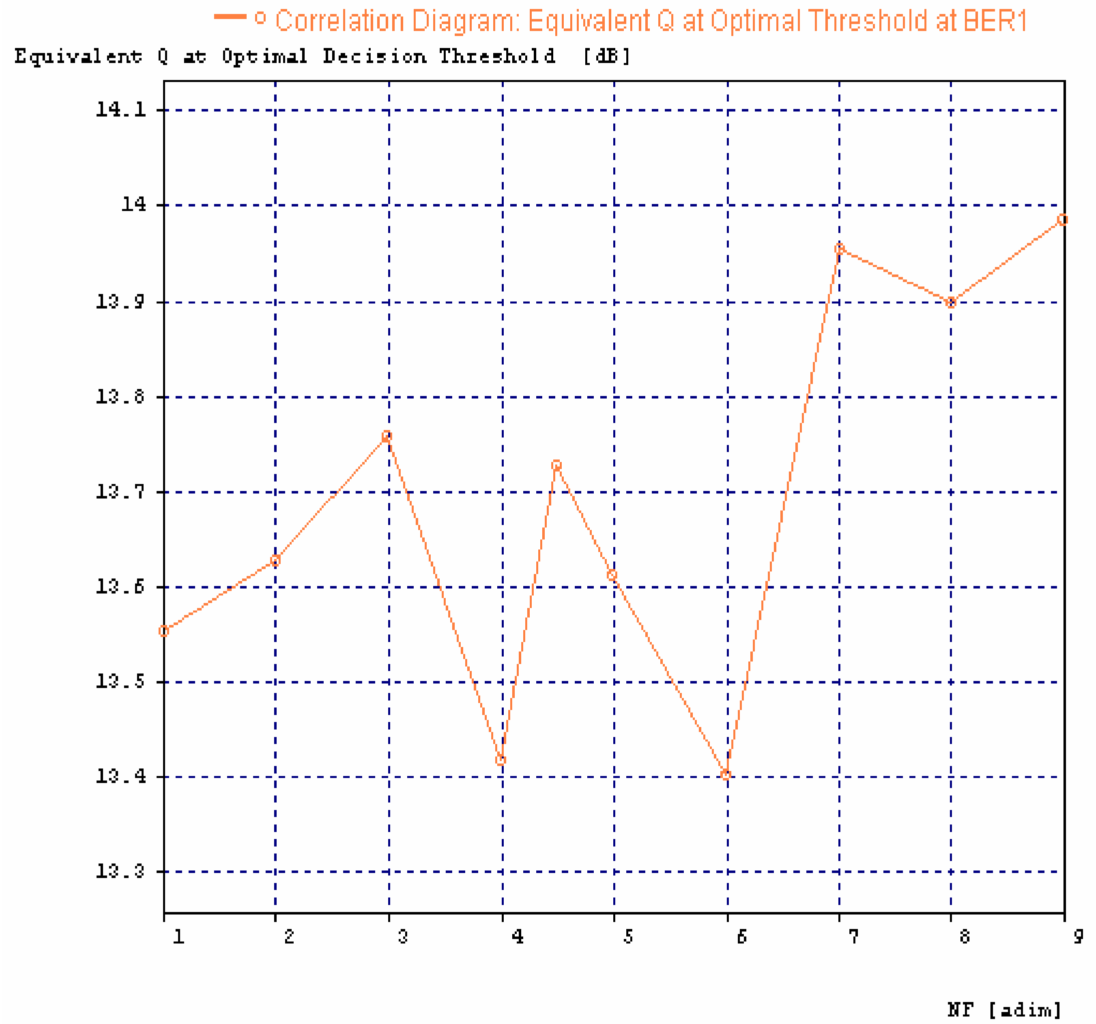


Fig. 5.3: Q-Value Vs NF for the link of Dhaka – Comilla

From this figure, it has been observed that within a NF range of 3 to 7 dB, the Q-Value lies within the **acceptable limit of 6.5 dB** (under this case Q-Value is even better ie. 13.4 dB, which is much higher than the acceptable value). The Q-value vs NF curve shows ripple owing to noise and jitter.

From the figure above, it has been observed that within the amplifier gain range of 10 to 15 dB, the Q-Value lies within the **acceptable limit of 6.75 dB** (under this case Q-Value is even better ie. 13.1 dB, which is much higher than the acceptable value). The curve shows ripples owing to noise and jitter present in the system.

Fig. 5.4 shows the BER Vs NF and Fig. 5.5 the Q-Value Vs NF of the EDFA for the 166 km long Dhaka-Feni link.

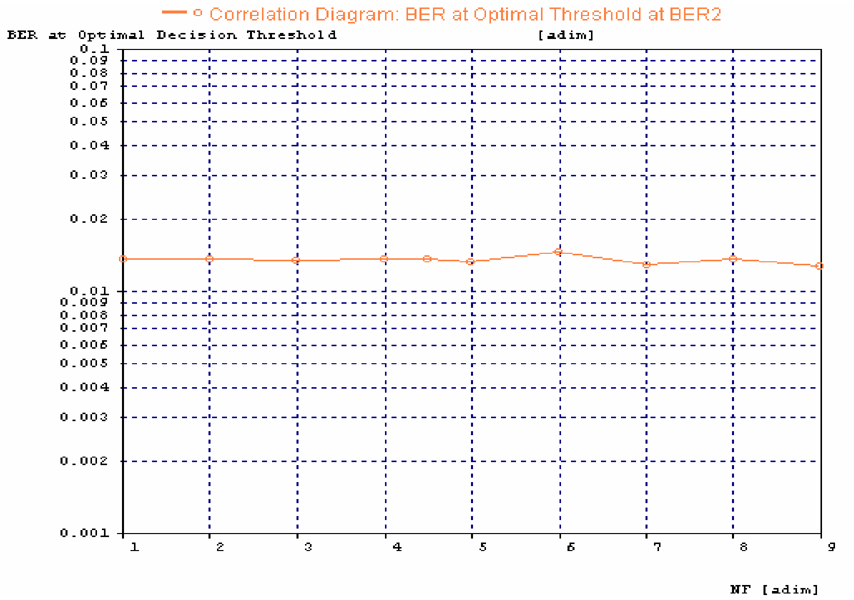


Fig. 5.4: BER vs NF of Dhaka – Feni Link

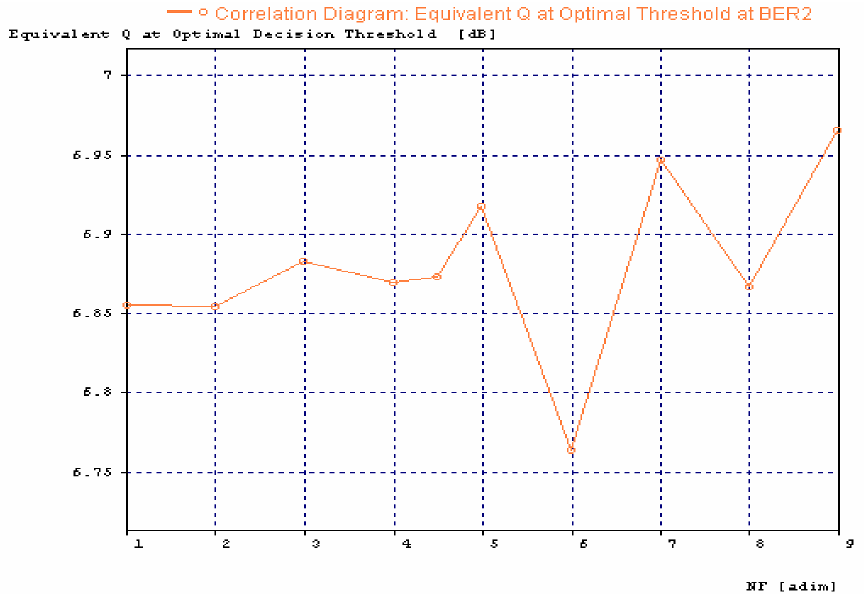


Fig. 5.5: Q-Value vs NF of Dhaka – Feni Link

For the combination of LASER-NRZ-EDFA-SM-APD, the parameters have been calculated for a distance of 167 km (Dhaka to Feni). From these figures, it has been observed that within the NF range of 2 to 9 dB, the BER performance is worsened (BER= 0.015 >> 10^{-6}), Q-value is 6.75 dB (slightly better and above the acceptable value).

Fig. 5.6 shows the BER Vs NF and Fig. 5.7 the Q-Value Vs NF of the EDFA for the 267 km long Dhaka-Chittagong link.

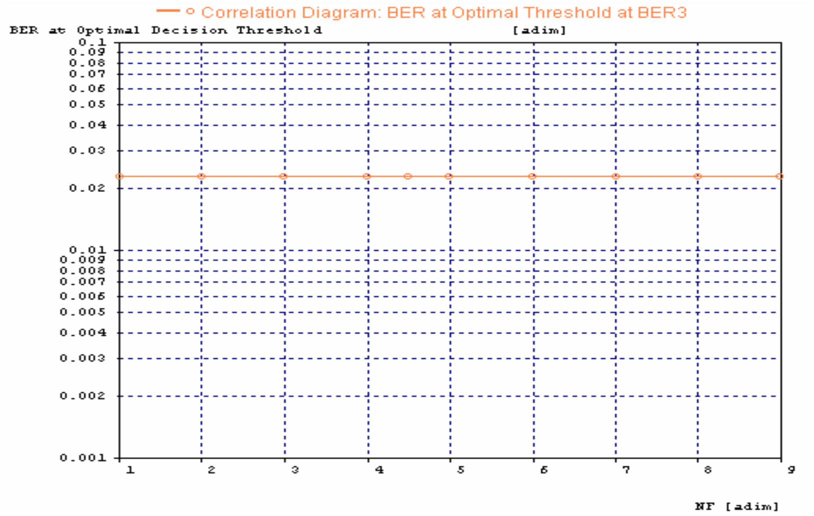


Fig. 5.6: BER Vs NF of Dhaka – Chittagong Link

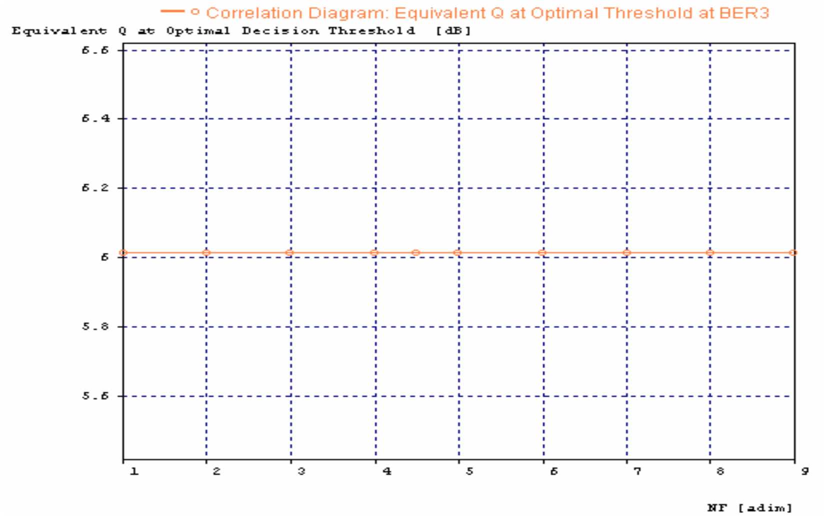


Fig. 5.7: Q-Value Vs NF of Dhaka – Chittagong Link

For the combination of LASER-NRZ-EDFA-SM-APD, the parameters have been calculated for a distance of 267 km (Dhaka to Chittagong). From these figures, it has been observed that within the NF range of 2 to 9 dB, the BER performance is worsened further (BER= 0.02 >> 10^{-6}), Q-Value is 6 dB (slightly below the acceptable value).

Fig. 5.8 shows the BER Vs NF and Fig. 5.9 the Q-Value Vs NF of the EDFA for the 367 km long Dhaka-Chiringa link.

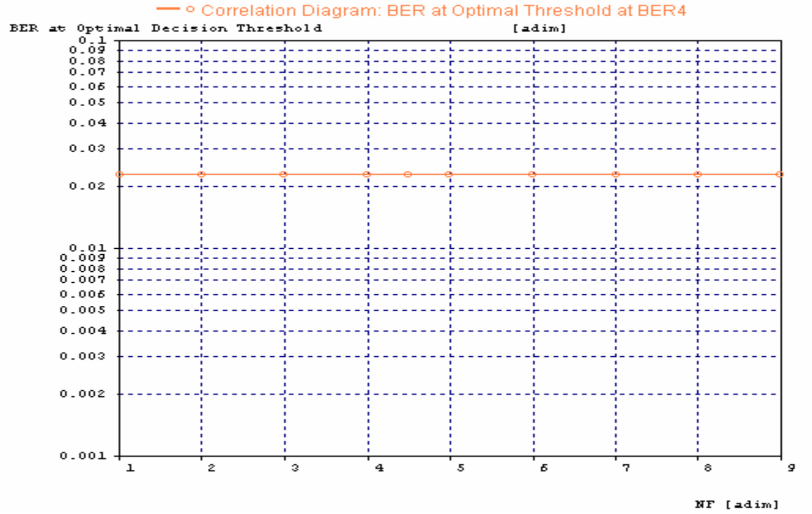


Fig. 5.8: BER Vs NF of Dhaka – Chiringa Link

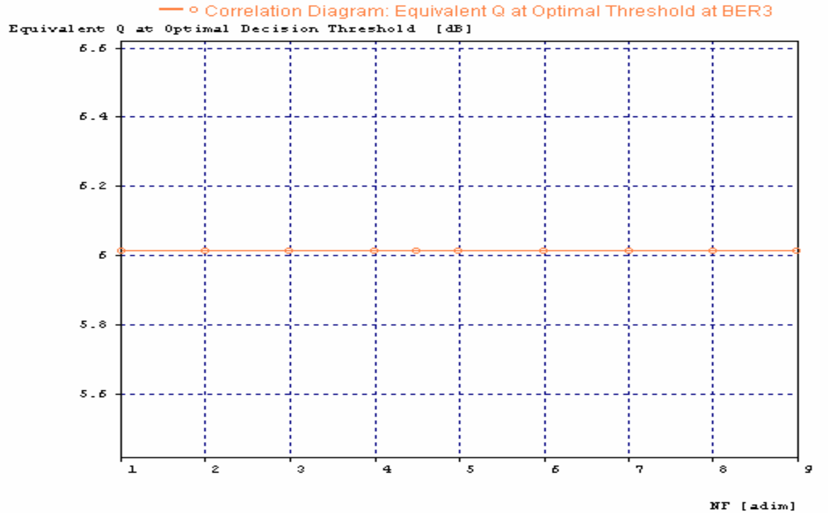


Fig. 5.9: Q-value Vs NF of Dhaka – Chiringa Link

For the combination of LASER-NRZ-EDFA-SM-APD, the parameters have been calculated for a distance of 367 km (Dhaka to Chiringa). From these figures, it has been observed that within the NF range of 2 to 9 dB, the BER performance is the worst one (BER= 0.02 >> 10^{-6}), Q-value is 6 dB (slightly below the acceptable value).

Fig. 5.10 shows the BER Vs NF and Fig. 6.11 the Q-Value Vs NF of the EDFA for the 5437 km long Dhaka-Cox's Bazar link.

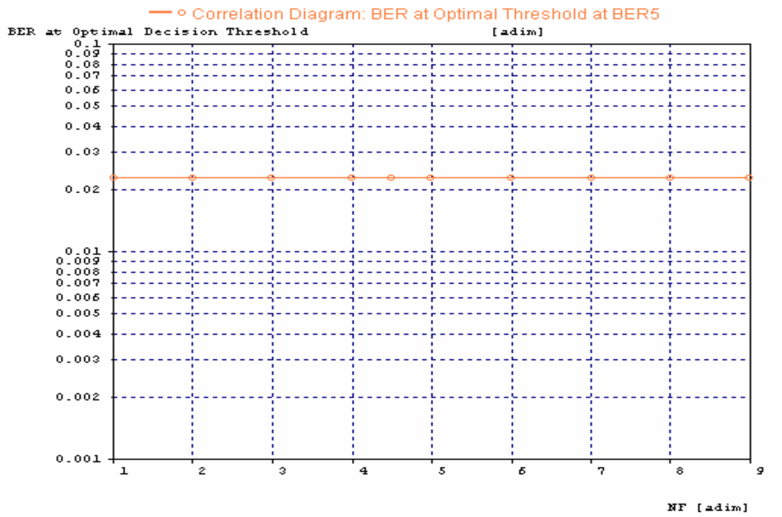


Fig. 5.10: BER Vs NF of Dhaka – Cox's Bazar Link

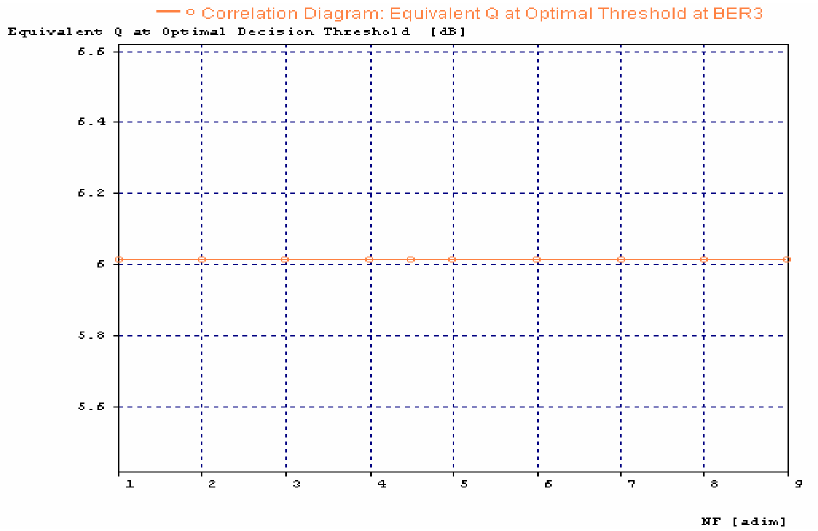


Fig. 5.11: Q-value Vs NF of Dhaka – Cox's Bazar Link

It has been calculated for a distance of 437 Km (Dhaka to Cox's Bazar) without DCF. It has been observed that under this case the worst of all BER is obtained (0.02) and Q-Value is 6.0 dB.

For the combination of LASER-NRZ-EDFA-SM-APD, the parameters have been calculated for a distance of 437 km (Dhaka to Cox's Bazar). From these figures, it has been observed that within the NF range of 2 to 9 dB, the BER performance is the worst one (BER= 0.02 >> 10^{-6}), Q-value is 6 dB (slightly below the acceptable value). It has already been mentioned earlier that the variation in the performance curves are owing to the presence of noise and jitter in the system.

5.4.2 Block Diagram and Simulation Results for the 10 Gbps Single-Channel Single-fiber Dhaka – Comilla – Feni – Chittagong – Chiringa – Cox's Bazar Link = 437 km Link (using DCF and EDFA) :

Block diagram of the 10 Gbps transmission link using EDFA and DCF is shown in Fig.5.12.

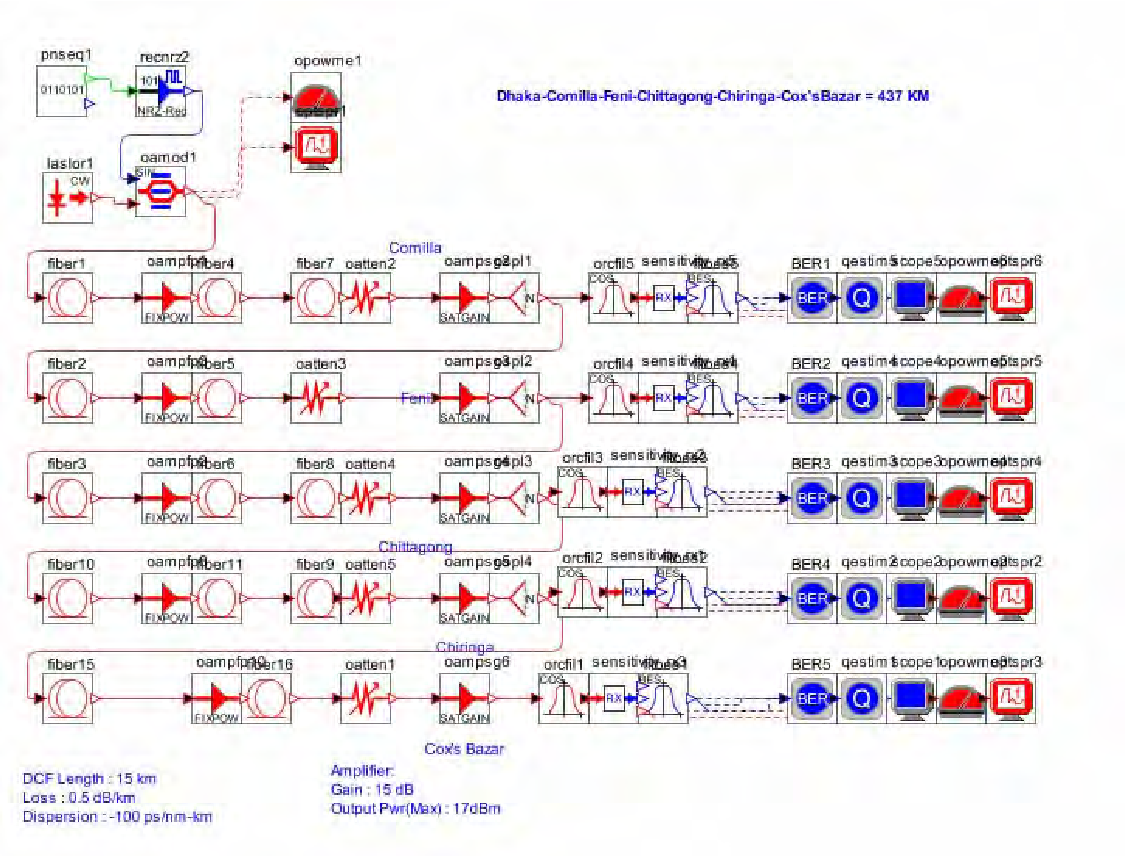


Fig. 5.12: Block Diagram of 10 Gbps Transmission Link (using DCF and EDFA)

The design assumes that DCF (Dispersion Compensator Fiber) and EDFA (Erbium Doped Fiber Amplifier) has been used.

The correlation diagram between BER Vs NF and Q-Value Vs NF for the link under current study are shown in Figures 5.13 to 5.22 (the corresponding data are included in Appendix-C (Table C.3 and C.4).

Fig. 5.13 shows the Q-Value Vs NF and Fig. 5.14 shows the BER Vs NF of the DCF and EDFA for the 103 km long Dhaka-Comilla link.

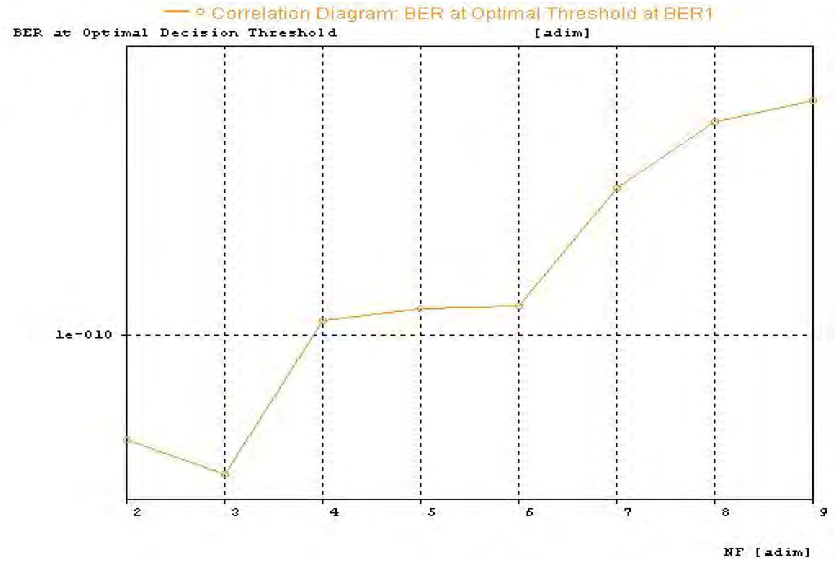


Fig. 5.13: BER Vs NF of Dhaka – Comilla Link

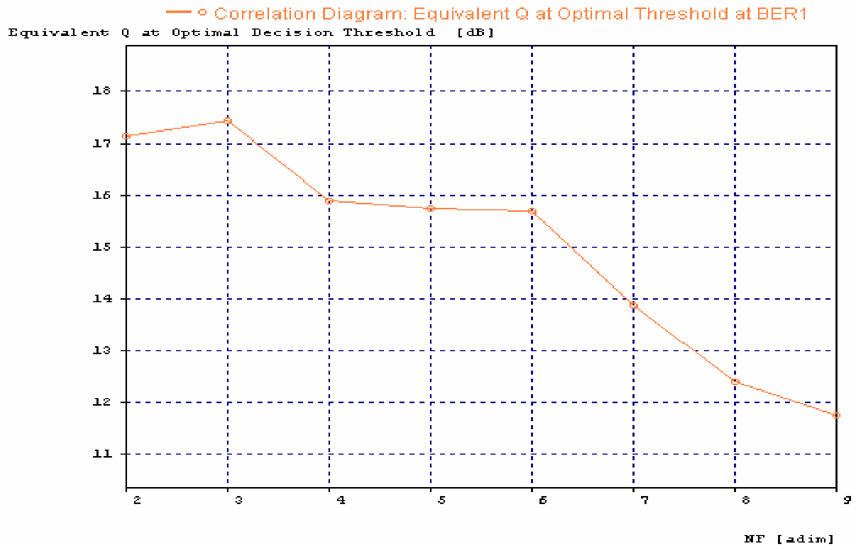


Fig. 5.14: Q-Value Vs NF of Dhaka – Comilla Link

For the combination of LASER-NRZ-DCF-EDFA-SM-APD, BER Vs. Noise Figure has been calculated for a distance of 103 km (Dhaka to Comilla). It has been observed that within a NF range of 3 to 7 dB, the BER lies within the **acceptable limit of 10^{-6}** (under this case BER is even better ie. range between 10^{-10} and 10^{-15}, which is much less than the acceptable value) and Q-Value is also better, which lies between 12 to 17 dB. Owing to the presence of noise and jitter, the BER performance curve is seen to have ripples.

Fig. 5.15 shows the BER Vs NF and Fig. 5.16 the Q-Value Vs NF of the DCF and EDFA for the 166 km long Dhaka-Feni link.

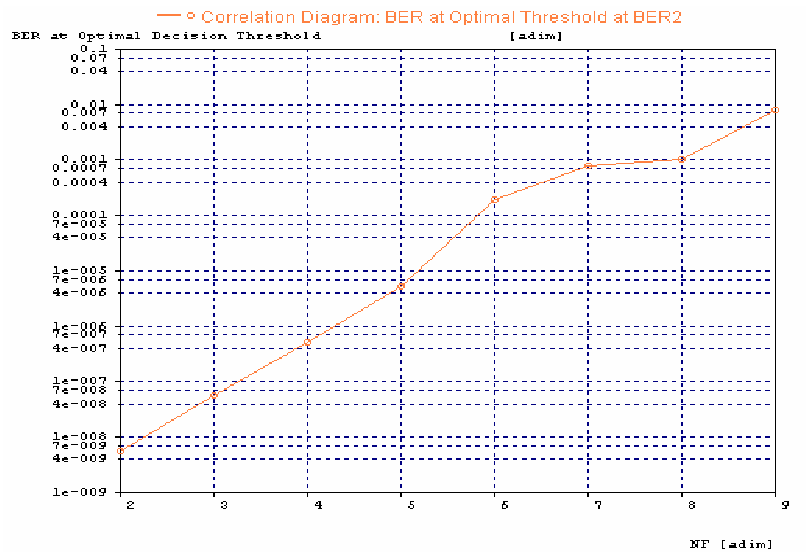


Fig. 5.15: BER Vs NF of Dhaka – Feni Link

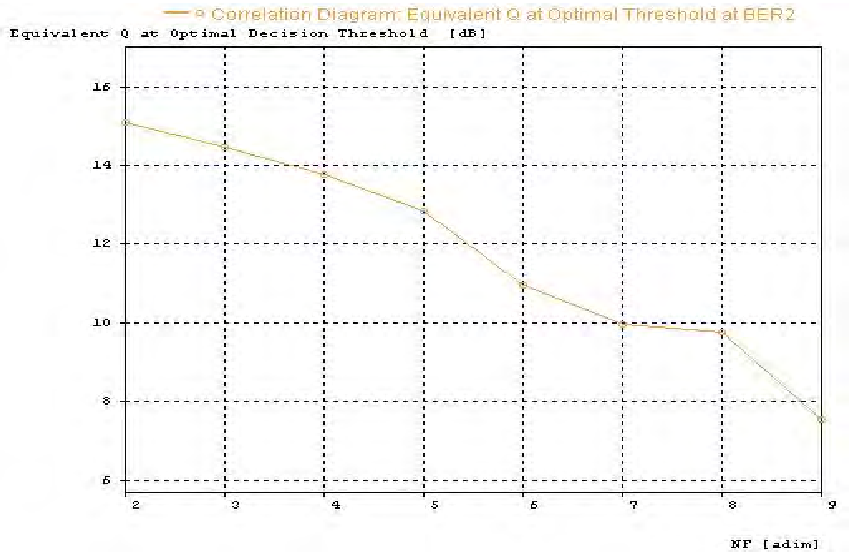


Fig. 5.16: Q-Value Vs NF of Dhaka – Feni Link

For the combination of LASER-NRZ-DCF-EDFA-SM-APD, the parameters have been calculated for a distance of 167 km (Dhaka to Feni). From these figures, it has been observed that within the NF range of 2 to 5 dB, the BER performance stays better (ie. BER range between 10^{-9} and 10^{-6}), whereas the NF between 5 to 9 dB, it gets worse (10^{-5} to 10^{-3}, ie. BER becomes higher than the acceptable limit). The Q-Value range is between 8 to 15 dB (better and above the acceptable value).

Fig. 5.17 shows the BER Vs NF and Fig. 5.18 the Q-Value Vs NF of the DCF and EDFA for the 267 km long Dhaka-Chittagong link.

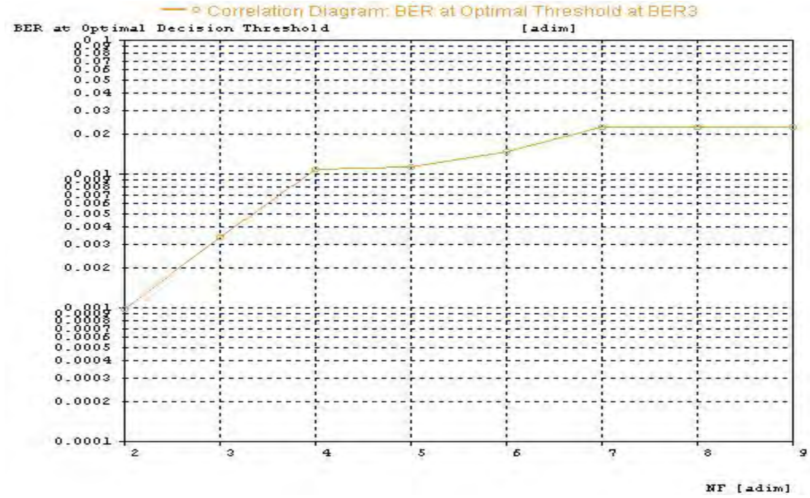


Fig. 5.17: BER Vs NF of Dhaka – Chittagong Link

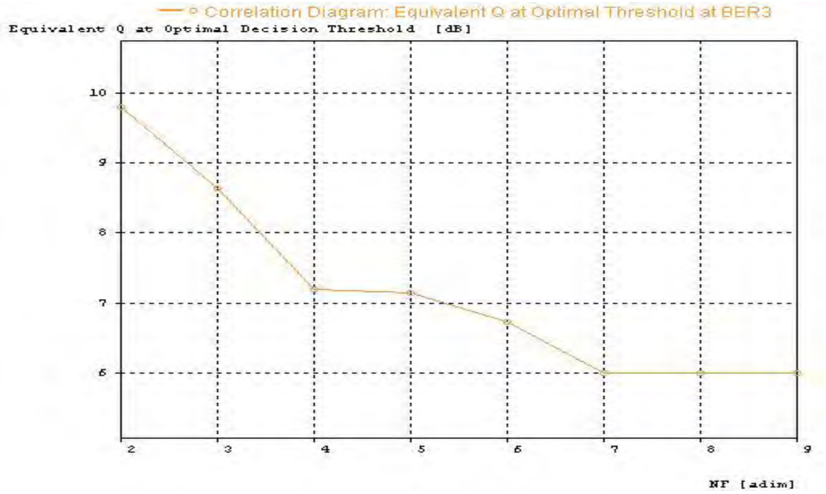


Fig. 5.18: Q-Value Vs NF of Dhaka – Chittagong Link

For the combination of LASER-NRZ-DCF-EDFA-SM-APD, the parameters have been calculated for a distance of 267 km (Dhaka to Chittagong). From these figures, it has been observed that within the NF range of 2 to 5 dB, the BER performance stays better (ie. BER range between 10^{-6} and 10^{-5}), whereas the NF between 5 to 9 dB, it gets worse (10^{-4} to 10^{-2}, ie. BER becomes higher than the acceptable limit). And within the NF rang of 2 to 6 dB, the Q-Value performance stays better (ie. range between 6.75 to 9.8 dB (better and above the acceptable value) and the Gain is 15 dB (still much better, as it lies above the acceptable limit of 6.75 dB).

Fig. 5.19 shows the BER Vs NF and Fig. 5.20 the Q-Value Vs NF of the DCF and EDFA for the 367 km long Dhaka-Chiringa link.

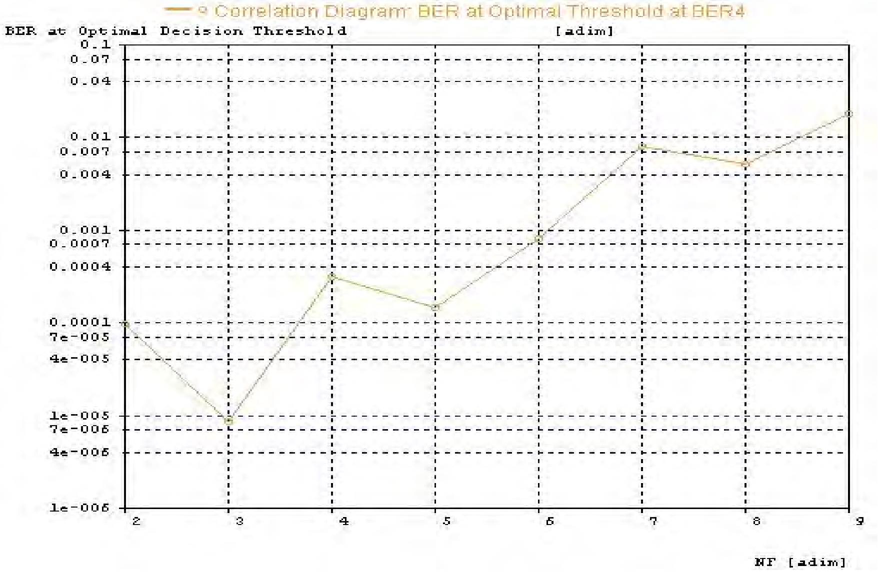


Fig. 5.19: BER Vs NF of Dhaka – Chiringa Link

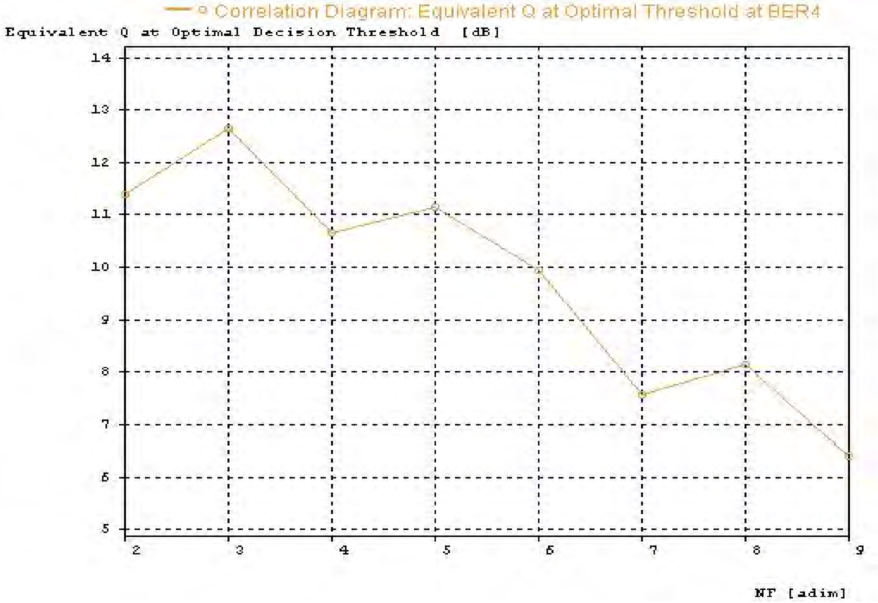


Fig. 5.20: Q-Value Vs NF of Dhaka – Chiringa Link

For the combination of LASER-NRZ-DCF-EDFA-SM-APD, it has been calculated for a distance of 367 km (Dhaka to Chiringa). From these figures, it has been observed that within the NF range of 2 to 5 dB, the BER performance stays better (ie. BER range between 10^{-7} and 10^{-6}), whereas the NF between 5 to 9 dB, it gets worse (10^{-5} to 10^{-3}, ie. BER becomes higher than the acceptable limit). And within the NF range of 2 to 8 dB, the Q-Value performance stays better (ie. range between 7.0 to 12.5 dB (better and above the acceptable value).

Fig. 5.21 shows the BER Vs NF and Fig. 5.22 the Q-Value Vs NF of the DCF and EDFA for the 367 km long Dhaka-Cox’s Bazar link.

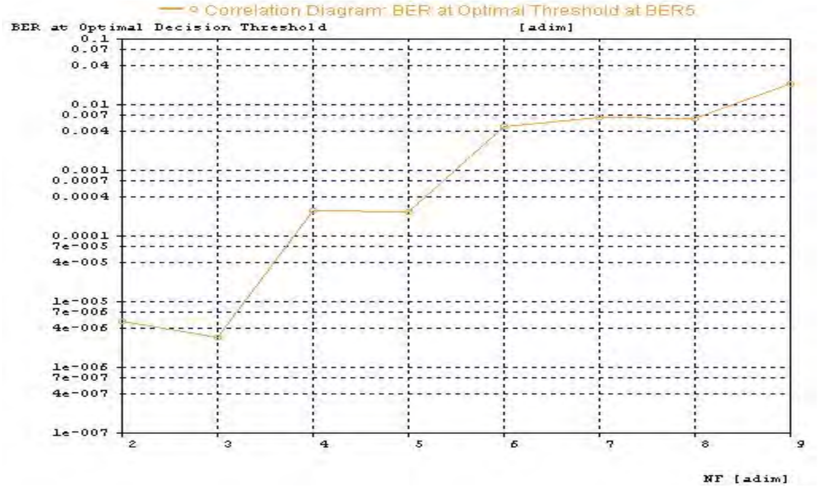


Fig. 5.21: BER Vs NF of Dhaka – Cox’s Bazar Link

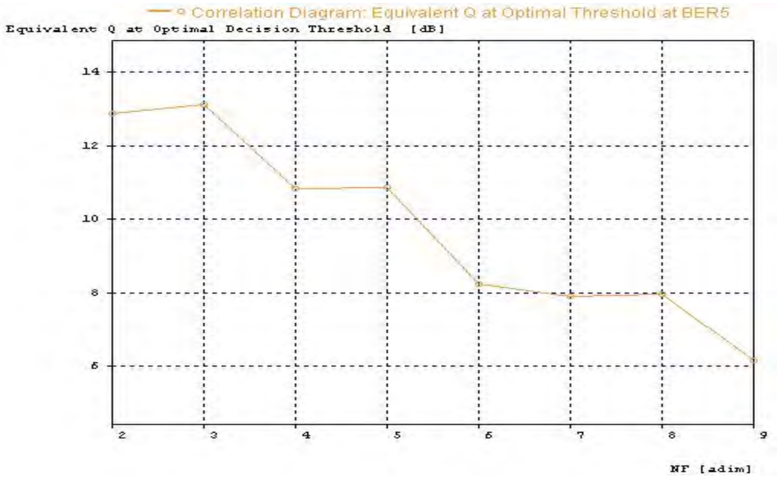


Fig. 5.22: Q-Value Vs NF of Dhaka – Cox’s Bazar Link

For the combination of LASER-NRZ-DCF-EDFA-SM-APD, it has been calculated for a distance of 367 km (Dhaka to Cox’s Bazar). From these figures, it has been observed that within the NF range of 2 to 5 dB, the BER performance stays better (ie. BER range between 10^{-8} and 10^{-6}), whereas the NF between 5 to 9 dB, it gets worse (10^{-5} to 10^{-3}, ie. BER becomes higher than the acceptable limit). And within the NF range of 2 to 8 dB, the Q-Value performance stays better (ie. range between 8.0 to 13.0 dB (better and above the acceptable value). It has already been mentioned earlier that the variation in the performance curves are owing to the presence of noise and jitter in the system.

5.4.3 Block Diagram and Simulation Results of 10 Gbps Single-Channel Single-Fiber Dhaka – Comilla – Feni – Chittagong – Chiringa – Cox's Bazar Link = 437 km Link (using DCF and SOA) :

Block diagram of the 10 Gbps transmission link using SOA and DCF is shown in Fig.5.23.

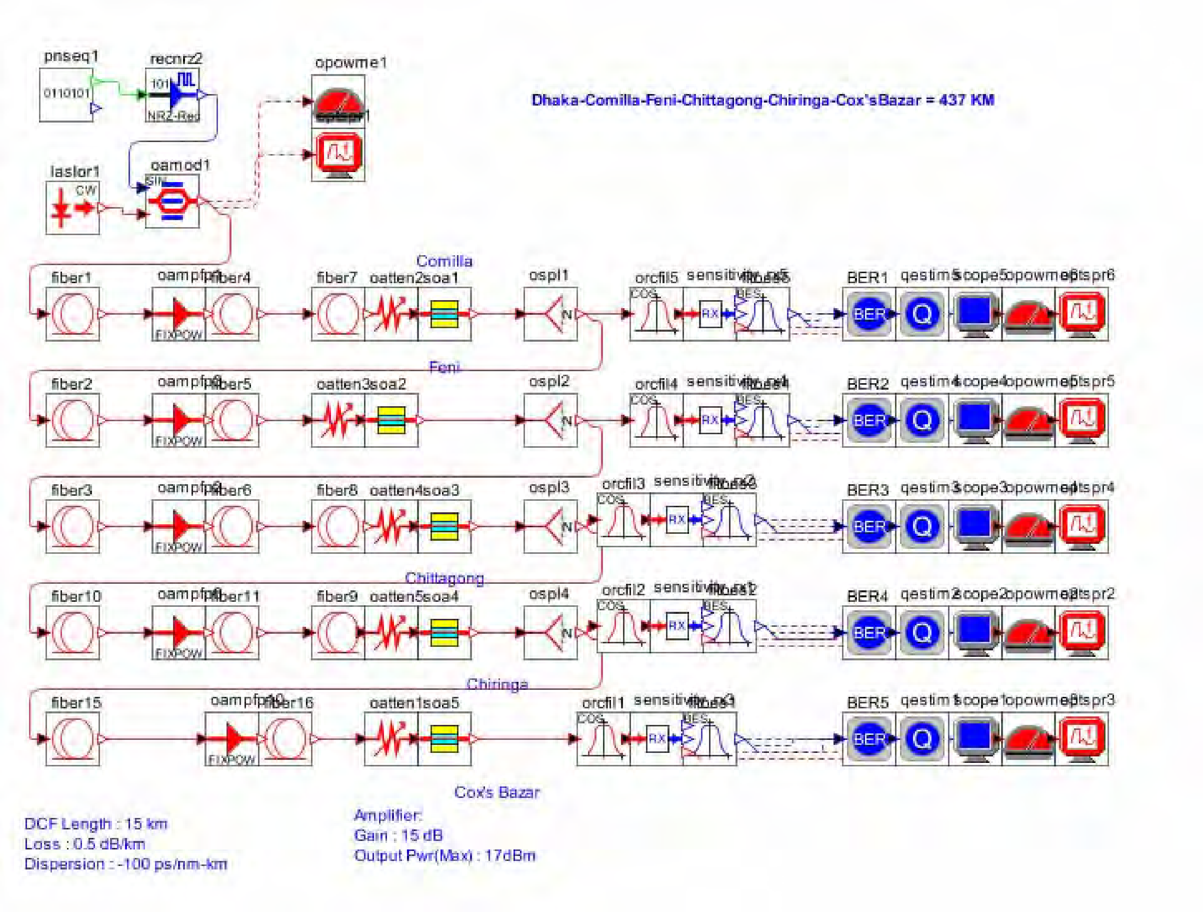


Fig. 5.23: Block Diagram of 10 Gbps Transmission Link with DCF and SOA

The design assumes that DCF (Dispersion Compensator Fiber) and SOA (Semiconductor Optical Amplifier) has been used.

The correlation diagram between BER Vs NF and Q-Value Vs NF for the link under current study are shown in Figs. 5.24 to 5.33 (the corresponding data are included in Appendix-C (Table C.5 and C.6).

Fig. 5.24 shows the Q-Value Vs NF and Fig. 5.25 shows the BER Vs NF of the DCF and SOA for the 103 km long Dhaka-Comilla link.

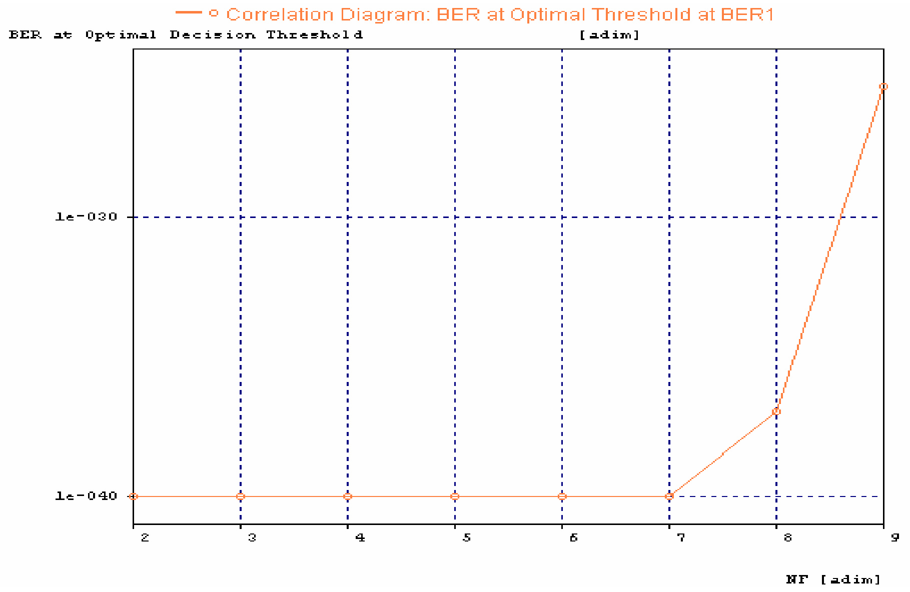


Fig. 5.24: BER Vs NF of Dhaka – Comilla Link

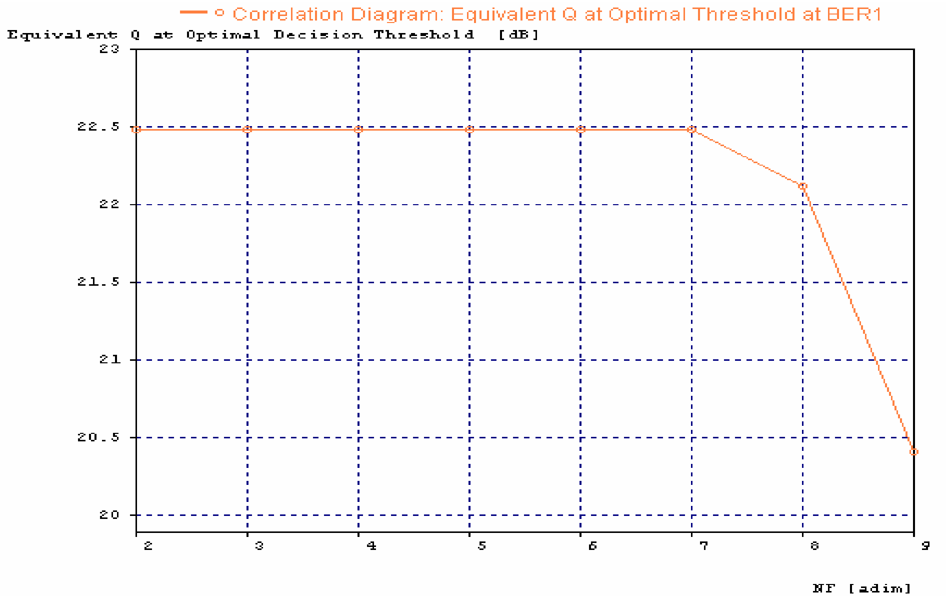


Fig. 5.25: Q-Value Vs NF of Dhaka – Comilla Link

For the combination of LASER-NRZ-DCF-SOA-SM-APD, BER Vs NF has been calculated for a distance of 103 km (Dhaka to Comilla). It has been observed that within a NF range of 2 to 9 dB, the BER lies within the **acceptable limit of 10^{-6}** (under this case BER is best ie. range between 10^{-40} and 10^{-25}, which is much less than the acceptable value) and Q-Value is also best, which lies between 20.5 to 22.5

dB. Owing to the presence of noise and jitter, the BER performance curve is seen to have ripples.

Fig. 5.26 shows the Q-Value Vs NF and Fig. 5.27 shows the BER Vs NF of the DCF and SOA for the 167 km long Dhaka-Feni link.

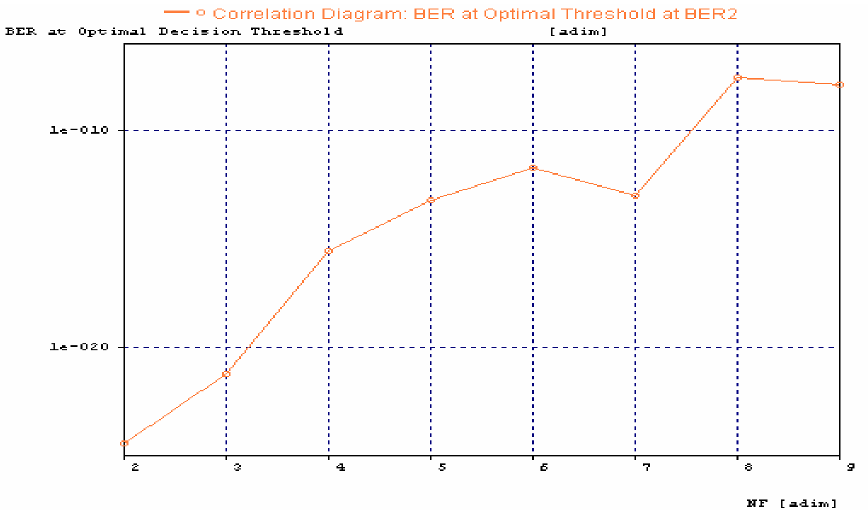


Fig. 5.26: BER Vs NF of Dhaka – Feni Link

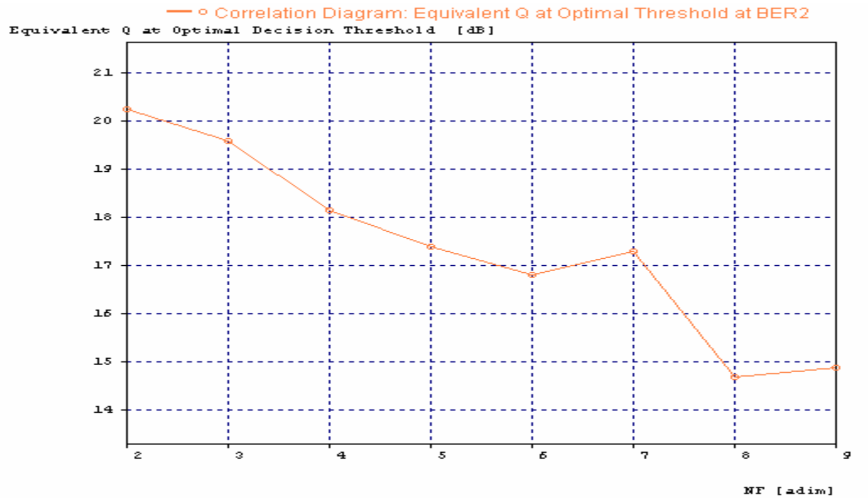


Fig. 5.27: Q-Value Vs NF of Dhaka – Feni Link

For the combination of LASER-NRZ-DCF-SOA-SM-APD, BER Vs NF has been calculated for a distance of 167 km (Dhaka to Feni). It has been observed that within a NF range of 2 to 9 dB, the BER lies within the **acceptable limit of 10^{-6}** (under this case BER is best ie. range between 10^{-30} and 10^{-8}, which is much less than the acceptable value) and Q-Value is also best, which lies between 14.5 to 20 dB.

Owing to the presence of noise and jitter, the BER performance curve is seen to have ripples.

Fig. 5.28 shows the Q-Value Vs NF and Fig. 5.29 shows the BER Vs NF of the DCF and SOA for the 267 km long Dhaka-Chittagong link.

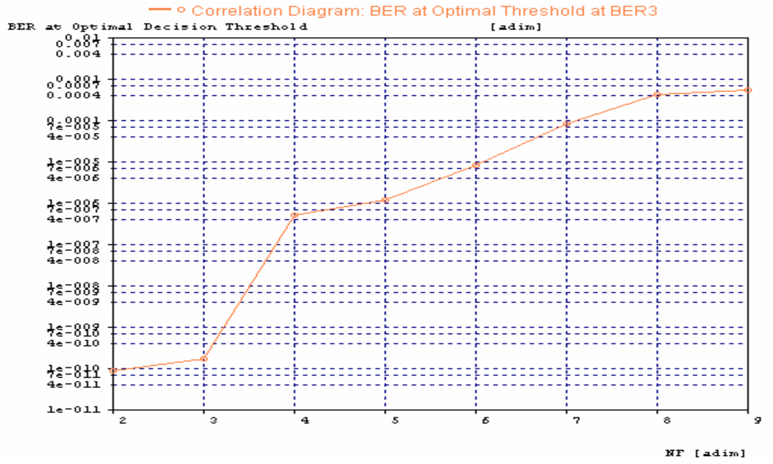


Fig. 5.28: BER Vs NF of Dhaka – Chittagong Link

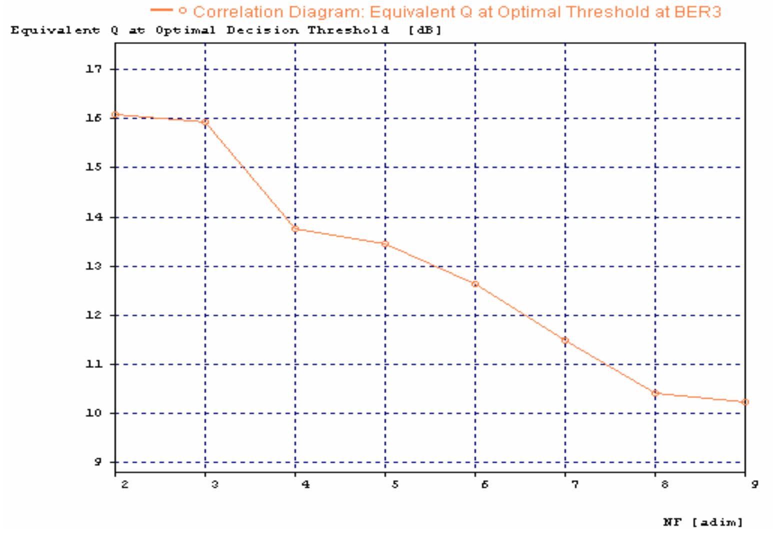


Fig. 5.29: Q-Value Vs NF of Dhaka – Chittagong Link

For the combination of LASER-NRZ-DCF-SOA-SM-APD, BER Vs NF has been calculated for a distance of 267 km (Dhaka to Chittagong). It has been observed that within a NF range of 2 to 9 dB, the BER lies within the **acceptable limit of 10^{-6}** (under this case BER is best ie. range between 10^{-12} and 10^{-7}, which is much less than the acceptable value) and Q-Value is also best, which lies between 10.25 to 16 dB. Owing to the presence of noise and jitter, the BER performance curve is seen to have ripples.

Fig. 5.30 shows the Q-Value Vs NF and Fig. 5.31 shows the BER Vs NF of the DCF and SOA for the 367 km long Dhaka-Chiringa link.

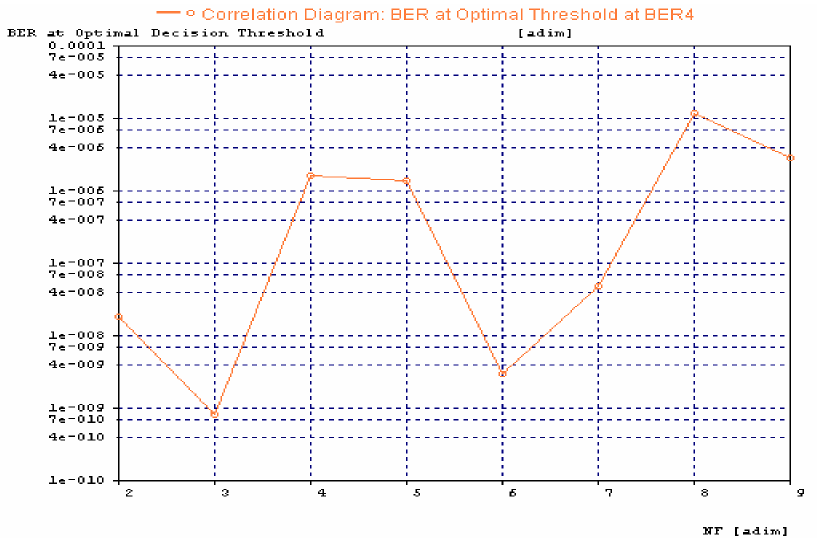


Fig. 5.30: BER Vs NF of Dhaka – Chiringa Link

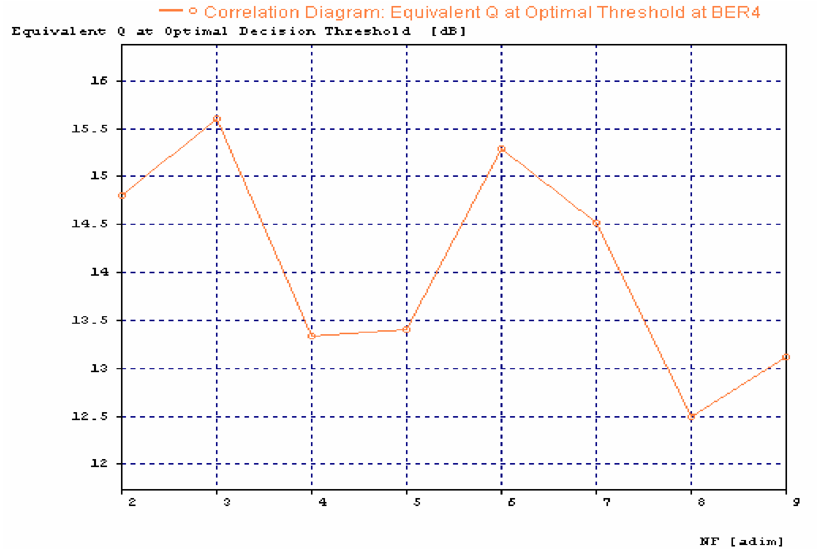


Fig. 5.31: Q-Value Vs NF of Dhaka – Chiringa Link

For the combination of LASER-NRZ-DCF-SOA-SM-APD, BER Vs NF has been calculated for a distance of 367 km (Dhaka to Chiringa). It has been observed that within a NF range of 2 to 9 dB, the BER lies within the **acceptable limit of 10^{-6}** (under this case BER is best ie. range between 10^{-11} and 10^{-6}, which is much less than the acceptable value) and Q-Value is also best, which lies between 12.5 to 15.5 dB. Owing to the presence of noise and jitter, the BER performance curve is seen to have ripples.

Fig. 5.32 shows the Q-Factor Vs NF and Fig. 5.33 shows the BER Vs NF of the DCF and SOA for the 437 km long Dhaka-Cox’s Bazar link.

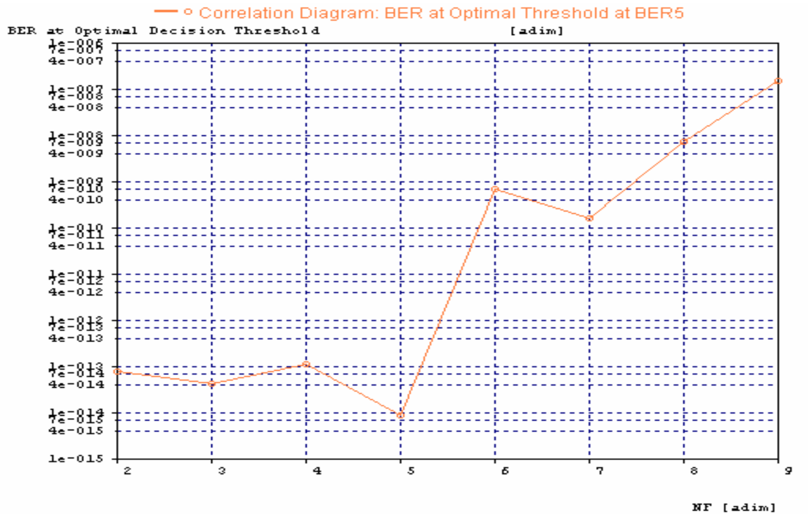


Fig. 5.32: BER Vs NF of Dhaka – Cox’s Bazar Link

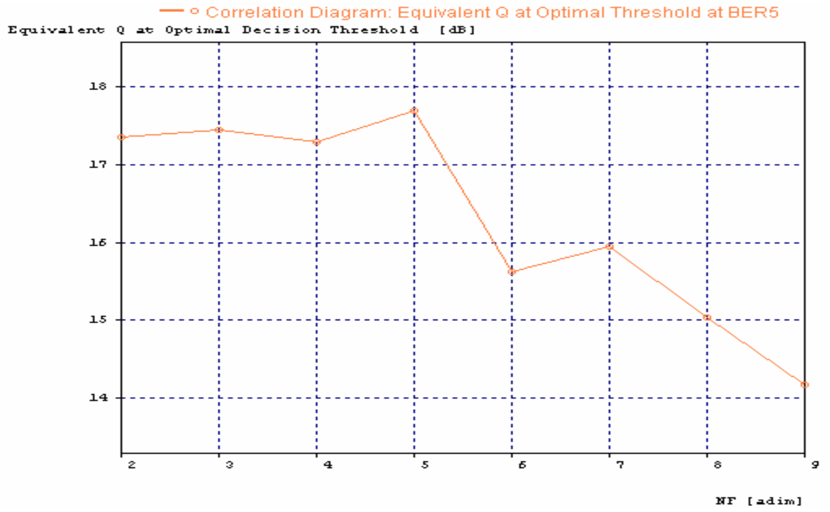


Fig. 5.33: Q-Value Vs NF of Dhaka – Cox’s Bazar Link

For the combination of LASER-NRZ-DCF-SOA-SM-APD, BER Vs NF has been calculated for a distance of 437 km (Dhaka to Cox’s Bazar). It has been observed that within a NF range of 2 to 9 dB, the BER lies within the **acceptable limit of 10^{-6}** (under this case BER is best ie. range between 10^{-14} and 10^{-6}, which is much less than the acceptable value) and Q-Value is also best, which lies between 13.5 to 16.5 dB. Owing to the presence of noise and jitter, the BER performance curve is seen to have ripples.

5.5 The Choice of Optimum Parameters

In the design of an optical link the following component combinations may be used.

1. Source + Modulation + Erbium Doped Fiber Amplifier + Single Mode Fiber + Detector
LASER-NRZ-EDFA-SM-APD

2. Source + Modulation + Semiconductor Optical Amplifier+ Single Mode Fiber + Detector
LASER-NRZ-SOA-SM-APD

3. Source + Modulation + Pre-Dispersion Compensator Fiber+ Amplifier+ Single Mode Fiber + Detector
LASER-NRZ-DCF-EDFA-SM-APD Or

Source + Modulation + Amplifier+ Post-Dispersion Compensator Fiber+ Single Mode Fiber + Detector
LASER-NRZ-EDFA-DCF-SM-APD

4. Source + Modulation + Pre-Dispersion Compensator Fiber+ Semiconductor Optical Amplifier+ Single Mode Fiber + Detector
LASER-NRZ-DCF-SOA-SM-APD Or

Source + Modulation + Semiconductor Optical Amplifier+ Post-Dispersion Compensator Fiber+ Single Mode Fiber + Detector
LASER-NRZ-SOA-DCF-SM-APD

The combinations **1.**, **3.** and **4.** have been used in the current design and subsequent simulation analysis.

From the graphs shown throughout Figures 5.1 to 5.33, the choice of the design was considered as follows.

For the combination of LASER-NRZ-EDFA-SM-APD with an amplifier gain of 15 dB, it is found that Q-Value for the above combination lies at an acceptable value up to a distance of 80 km and less. The NF lies within 4 to 6 dB (ie. the optimum and reliable).

However, after 80 km and above; however, not exceeding another 80Km (i.e. for a total link length of 160 km), DCF must be used to avoid dispersion and BER degradation. Thus, the combination of LASER-NRZ-DCF-EDFA-SM-APD is suitable for the part of a link, which is above 80 km in length. The NF is seen to lie within 6 to 7 dB (ie. the optimum and reliable) for better performance of the system.

One can also use a Semiconductor Optical Amplifier as well. If the combination of LASER-NRZ-DCF-SOA-SM-APD is used after 80 km, the NF lies within 7 to 9 dB (which is acceptable in case of SOA) and offers the best performance of the system. However, the cost will be much higher.

Therefore, the second choice as mentioned above, should be the optimum choice for designing an optical link in Bangladesh. Table 5.8 shows the comparative hardware complexity between the BTCL link and the proposed optimum link.

Table 5.8: Comparative Hardware Complexity between the Links of BTCL and the Proposed Optimum Link

Properties for	**BTCL Link**					**Proposed Optimum Link**				
	S-1	**S-2**	**S-3**	**S-4**	**S-5**	**S-1**	**S-2**	**S-3**	**S-4**	**S-5**
Distance (km)	103	63	101	100	70	103	63	101	100	70
After 80 km is DCF used?	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes
No. of EDFAs	1	1	1	1	1	1	1	1	1	1
NF	4.5	4.5	4.5	4.5	4.5	7	8	7	7	8
BER	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}
Q-Value	13.7	13.7	13.7	13.7	13.7	13.8	12.4	13.8	13.8	12.4

If DCF is used, signal degradation will be less, and the improved signal can tolerate a high NF. One can then use an EDFA of a higher-valued NF (lower cost) to achieve the desired BER.

A DCF and an EDFA (with a higher-valued NF) is much less costlier than a single EDFA of a lower-valued NF. Thus, an appropriate DCF and EDFA combination will perform satisfactorily with a lower cost. However, to add a DCF into the system an additional PoP (point-of-presence) will be required.

CHAPTER 6

CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

Since the advent of optical communications, a great technological effort has been devoted to the exploitation of the huge bandwidth of optical fibers. Starting from a few Mbps single channel systems, a fast technological development yielded the present 10 Gbps per channel WDM systems. Such a pace in technological progress must be supported or better preceded, by an analogous evolution of the theory. Our goal in the current research work was to analyze the optical system strictly from the point of view of communications theory.

6.1 Summary of the Major Contributions

A comprehensive study has been performed, for the first time, on the existing capacity of the deployed submarine cable connectivity and its present scenario in terms of its use in Bangladesh. The results of the survey, that has been carried out as part of the study, reveal that the fixed phone subscribers' growth in Bangladesh varies between 0.8 to 2 percent, whereas that of mobile phone varies between 2.5 to 5 percent monthly. However, it is now heading towards an almost steady level.

A demand forecasting model has been developed for the telecommunications bandwidth requirement relating the four major user classes, such as, voice, internet, mobile operators and other new applications.

An extensive study has been carried out to survey the existing network facilities, its access networks, redundancy schemes and QoS issues etc. of BTCL. The major lapses of the existing network have also been identified, especially, at the levels of resource allocation and redundancy measures adopted.

After a careful study and proper analysis, an optimum network plan has been proposed for the major inter-city routes of the optical fiber backbone network. The proposed network plan includes the deployment of redundant routes or paths for ensuring a reliable digital communication.

Analytical formulae were developed for various Quality of Service (QoS) parameters, such as, BER, Q-factor and NF are then formulated for an optical link to be used in the proposed network plan.

Part of the backbone network, connecting Dhaka to Cox's Bazar landing station, was then simulated using the OptSim simulator for the existing BTCL link, and two other link designs as proposed in the current research. Appropriate compensation techniques and various types of modulation schemes were also applied while performing the simulation. The simulations were performed to understand the behavior of the 40 Gbps single fiber Multi-channel DWDM system.

The hardware complexity and the QoS parameters were compared between the designed links and the existing link of BTCL at hand. The optimum design parameters offer lower hardware complexity and better performance.

The findings of the reserch would help the planners and decision makers to design and better utilize the full potential of the submarine cable connectivity in Bangladesh. Some very basic technical and socio-economic problems of submarine cable connectivity, and the challenges of utilizing its full potential are also identified here.

Awareness of the current technology, the ability to use it and building the appropriate infrastructure are the key issues to the growth of ICT in Bangladesh. The information presented in this case study would also be very useful for any other developing country that is in the similar status as Bangladesh.

6.2 Recommendations

As part of the current study, an extensive survey was carried out, which reveals that at present the BTCL (Bangladesh Telecommunications Company Limited) has no high speed Internet connectivity access network to provide services directly to the customer's end. They only provide connectivity port at their end as per user demand. Many private companies like Telnet, Next Generation, Metronet, Ektoo, Alap, etc. have established their own high speed Internet/data access network (optical access network) to support end users. Customers are now dependent on these companies. Government or BTCL is yet to setup a substantial number of optical access networks in Bangladesh. However, the Multi-Service Access Network (MSAN) project is going to spread out optical access networks shortly in Bangladesh. At Present, local transmission or backbone network is yet to cover the whole country. Also, no redundant local backbone and international backbone networks are available in Bangladesh. From the survey, we have come to learn that the local backbone network get cut off 10 to 15 times yearly, and the international backbone network 2 to 3 times. Again, it takes 6 to 10 hours and 7 to 10 days, respectively, to repair and resume the local and international backbone networks.

A better optical fiber infrastructure is the key requirement to avail full potential of the submarine cable capacity. In Bangladesh, many private operators have implemented optical fiber networks and radio links for providing voice and data (Internet) services to their customers. Thus resources have been duplicated and they remain under-utilized. The proposed backbone network may be implemented by sharing all the available resources of both the government and private parties. Such a design would ensure avoidance of resource duplication and minimization of the overall cost.

Redundant routes have to be established at all possible levels to ensure quality and reliable service to the end users. This means that in case of any unwanted cable failure, data traffic could be re-routed so that they would reach their intended recipients without failure.

To meet the growing need of bandwidth, appropriate measures have to be taken to tackle the issues in collaboration with all the parties involved, and thereby harness the maximum benefit of the submarine cable connectivity.

When the maximum capacity of the submarine cable could be utilized, one would then be able to make a phone call, check his/her e-mail, watch television or can surf the web with the help of the high speed Internet facilities.

The development of appropriate access networks will help the growth of the ICT sector of Bangladesh. However, there are other factors also that should be taken into consideration while adopting the proposed solutions. It may not be possible to bridge the digital divide with other developed countries very soon, but it is important to prevent it from deepening, as a gesture, attempts should be made to narrow it down as much as possible. To reduce this gap of digital divide, the following points could be considered:

- Telephone and PC density should be raised to a satisfactory level which is now under way.
- Digital divide in urban-rural and national-international level should be narrowed down.
- ICT policy should be implemented to its full extent. Bangladesh already has an ICT policy but the materialization of all the clauses are yet to be taken place.
- Awareness should be created among the policy makers on the potential of ICT as an important element of its development.
- Government should take steps to build the basic infrastructures in the rural areas: electricity, telephone, and Internet connectivity.
- Have to create ICT awareness in rural areas so that people at the grass root level can have access to education and knowledge.
- Have to set up Public Key Infrastructure (PKI) in support of e-commerce and e-government.
- Set up high speed fiber-optic backbone up to upazilla-level (sub-district-level).
- Internet facilities have to reach sub-urban and district levels.
- Should improve quality of ICT education by improving laboratory and library facilities, Internet access to digital libraries and International Journals and databases (done up to some extent).
- Develop ICT training curricula for employees in order to ensure that they become computer literate and are able to utilize computers for conducting their tasks.
- To meet the vision and objectives of the ICT policy, it is necessary to develop skilled manpower in public sectors by imparting proper training.
- Man-machine ratio should be upgraded.
- There is a need for holistic approach to the creation of ICT infrastructure.
- Encouraging and assisting mass-people with computer literacy.
- Establishment of community information and communication centers to

bridge the digital divide between urban and rural population.

- Encourage private investments in telecommunication and information technology sectors.
- Joint ventures between local and foreign entrepreneurs in the ICT sector could be promoted.
- Electronic voting system and general purpose identity cards for all citizens should be utilized (recently identity cards are provided by the government and e-voting is supposed to be launched soon).

The digital divide problem will always be there if

- many languages cannot be processed and stored by computers
- the personal computers and the software are very expensive
- the cost of bandwidth is high all over the world
- the ability to use ICT is not increased notably

Hence, appropriate steps should be taken in the near future keeping all these recommendations and points in mind. Only then, the effort of enhancing the current infrastructure would show up positive results.

6.3 Suggestions for Future Work

Approximations have been used throughout the work in this thesis to simplify the problems. The non-linear effects of the fiber have been neglected in the analysis. In future, analysis and simulation may be undertaken considering the effects of fibre non-linearity.

In the single-channel analysis, we confined ourselves within the interaction of linear effects alone without considering fiber chromatic dispersion. Linear effects due to dispersion could be incorporated as an extension of the current study to analyze the performance degradation.

For the occurrences of high instantaneous Delay Group Dispersion (DGD) in an optical transmission system, signal quality may be intolerable and will result in both linear and nonlinear induced outage. Such outages may significantly affect network availability for higher bit rates (*i.e.* 10 Gbps, 40 Gbps and higher). One can estimate the probability that the system no longer functions properly; the outage probability, which must be very low, typically 10^{-6} – 10^{-5}, corresponding to a few seconds to a few minutes per year. The maximum link DGD that a receiver can tolerate before the signal degradation becomes unacceptable depends on a variety of factors; including modulation format, optical SNR and receiver design. Therefore, in the design of a robust long-haul fiber-optic network, derivation and analysis of the system outage probability due to both linear and nonlinear effects could be undertaken as further extension of this research.

Further research can also be initiated to develop an analytical model for single fibre multi-channel system with probability of bit error/packet error rate in an IP over WDM network and optical burst switching networks, considering the influence of the above mentioned system impairments. Still, a lot of room is available for the researchers in the area of fiber optics. The impact of nonlinear effects like stimulated Raman scattering and stimulated Brillouin scattering may also be considered in a WDM system.

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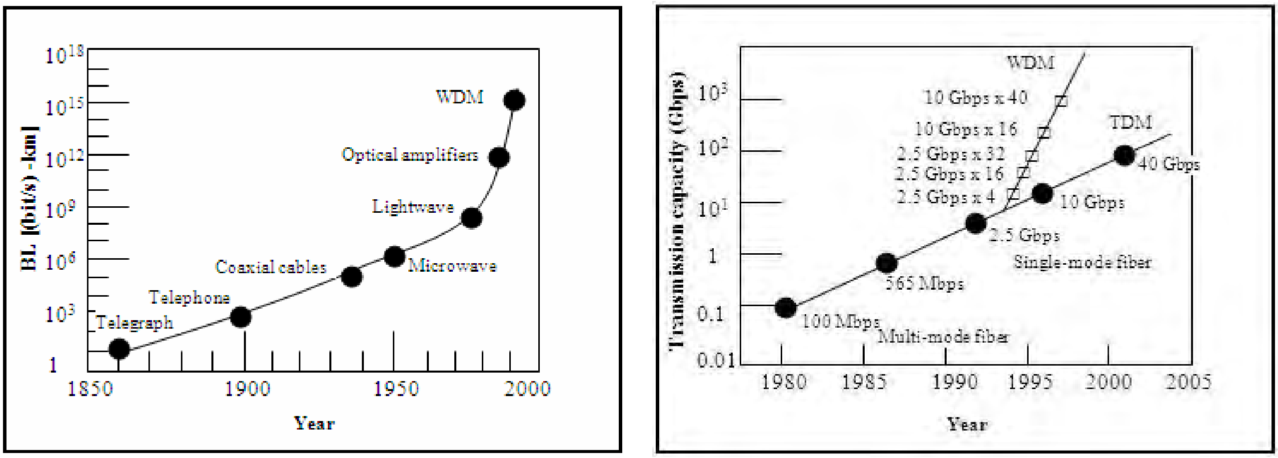
APPENDIX - A

Historical Perspective of the Optical Fiber Communication Systems

Even though an optical communication system had been convinced in the late 18th century by a French Engineer Claude Chappe who constructed an optical telegraph, electrical communication systems became the first dominant modern communication method since the advent of telegraphy in the 1830s [32]. Until the early 1980s, most of the fixed (non-radio) signal transmission were carried by metallic cable (twisted wire pairs and coaxial cable) systems. However, large attenuation and limited bandwidth of coaxial cable limited its capacity upgradation. The bit rate of the most advanced coaxial system, which was put into service in the United Sates in 1975 was 274 Mbps. At around the same time, there was a need of conversion from analog to digital transmission to improve transmission quality, which requires further increase of transmission bandwidth. Many efforts were made to overcome the drawbacks of coaxial cable during 1960s and 1970s. In 1966, Kao and Hockham proposed the use of optical fiber as a guiding medium for optical signal. Four years later, a major breakthrough occurred when the fiber loss could be reduced to about 20 dB/km from previous values of more than 1000 dB/km [33]. Since that time, optical communication technology has developed rapidly to achieve larger transmission capacity and longer transmission distance. The capacity of transmission has increased about 100 fold in every 10 years.

The first generation of optical communication was designed with multi-mode fibers and direct bandgap GaAs light emitting diodes (LEDs), which operate in the 800 nm – 900 nm wavelength range. Compared to the typical repeater spacing of coaxial system (~ 1 km), the longer repeater spacing (~10 km) was a major motivation. Large modal dispersion of multi-mode fibers and high fiber loss at 850 nm (> 5 dB/km) limited both the transmission distance and bit rate. In the second generation, multi-mode Fibers were replaced by single-mode fibers, and the center wavelength of light sources was shifted to 1300 nm, where optical fibers have minimum dispersion and lower loss of about 0.5 dB/km [33]. However, there was still a strong demand to increase repeater spacing further, which could be achieved by operating at 1500 nm, where optical fibers have an intrinsic minimum loss around 0.2 dB/km. Larger dispersion in 1550 nm window delayed moving to a new generation until dispersion shifted fiber became available. Dispersion shifted fibers reduce the large amount of dispersion in the 1550 nm window by modifying the index profile of the fiber while keeping the benefit of low loss at the 1500 nm window.

Most of the currently deployed fiber optic systems are based on the second and third window of operating wavelength. The operating wavelengths of an optical fiber link are determined by the attenuation and dispersion in fiber and availability of optical communications devices and components. The low-loss transmission windows centered about 1300 nm and 1550 nm. Each window covers a bandwidth of 10 to 15 THz. Each of the windows can be used for transmission of large number of optical carriers operating at a bit rate of 10 Gbps or more. The development of various types of telecommunication systems since 1850 is depicted in Fig. A.1 (a) and the evolution of optical transmission system capacity with and without wavelength division multiplexing (WDM) is shown in Fig. A.1 (b).



(a) (b)

Fig. A.1: (a) Development in telecommunication systems; (b) Evolution of transmission capacity of optical transmission systems.

The historical development of various generations of optical transmission system i.e. dark fiber capacity is illustrated in Fig. A.2.

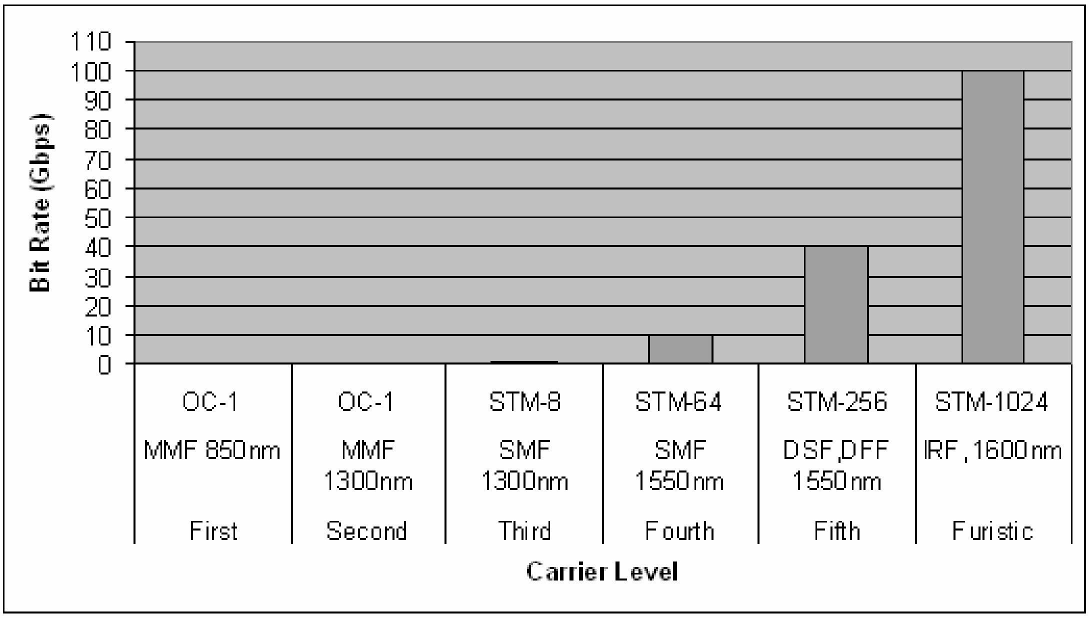


Fig. A.2 : Dark fiber capacity growth.

An important advancement was that an erbium-doped single mode fiber amplifier (EDFA) at 1550 nm was found to be ideally suited as an amplifying medium for modern fiber optic communication systems. Invention of EDFA had a profound impact especially on the design of long-haul undersea system, The EDFA band, or the range of wavelengths over which the EDFA can operate, proved to be an important factor in fixing the wavelength of operation of present day fiber optic systems. The EDFA band is wide enough to support many wavelengths simultaneously. This led to the development of wavelength division multiplexing (WDM) systems or the simultaneous propagation of several wavelengths of light through a fiber, where each wavelength can carry a different data stream.

In the late 1990s, the demand for bandwidth, especially with the huge growth of the Internet, fueled a rapid increase in the data rates. As the number of channels and data rates rose, certain phenomenon such as chromatic dispersion (CD) and nonlinearities began to show up as obstacles. CD being deterministic in nature could be effectively compensated for by using special fibers called dispersion compensating fibers and other novel devices [34 - 38].

The chronological development in optical transmission system is shown in Table A.1.

Table A.1 : Chronological development in optical transmission system

Particulars	**First Generation (1977)**	**Second Generation (1980)**	**Third Generation (1990)**	**Fourth Generation (1995)**	**Fifth Generation (2000)**	**Furistic Optical Tx System**
Fiber Type	MMF 850 nm	MMF 1300 nm	SMF 1300 nm	SMF 1550 nm	DSF, DFF Optical Soliton 1550 nm	IRF, 1600 nm Optical Soliton
Attenuation	2 dB/km	1 dB/km	< 1 dB/km	0.3 dB/km	<0.2 dB/km	0.02 dB/km
Bit Rate	45 Mbps	45 Mbps	1000 Mbps	10 Gbps	10 – 50 Gbps	100 Gbps
Repeater spacing	10km	30 km	40 km	SOA 100 km	SOA, EDFA WDM 1000km	Raman Amplifier, EDFA OTDM-WDM 5000 km
Limitations	MM Dispersion, Chromatic Dispersion	MM Dispersion	Chromatic Dispersion	Chromatic Dispersion	PMD, XPM, FWM, Jitter, Crosstalk	PMD, XPM, FWM, Jitter, Crosstalk

Multi-Channel Optical Transmission Systems:

The first generation of optical communication system was deployed during 1970’s at an operating wavelength of 850 nm due to availability of semiconductor lasers of the same wavelength region and multimode fiber. With progress in the development of lasers of longer wavelength and low loss single mode fiber, the second generation of optical communication system started during 1980s at about 1330 nm operating window of silica fiber and the third generation of system operation started during 1990s with the deployment of Erbium-doped fiber amplifiers (EDFAs) in the third operating window of 1550 nm of silica fiber where the fiber loss is found to be minimum of 0.2 dB/km.

Multichannel transmission over a single optical fiber can exploit the enormous bandwidth of fiber which is of the order of few hundred tera-hertz. Rapid development of optical multiplexing devices for wavelength division multiplexing (WDM) make it possible to realize multi-wavelength transmission over a single single-mode fiber over thousands of kilometers with periodic amplification using Erbium doped fiber amplifiers in cascade. Development of semiconductor optical amplifier (SOA), Erbium doped fiber amplifier (EDFA), Optical Add-drop multiplexer (OADM), tunable laser sources.

Development of WDM components

The rapid development in optical transmission system is due to the development in optical devices and components required for WDM transmission. The optical amplifiers were first deployed to replace the repeaters during 1994. In a optical repeater, the optical signal is converted to electrical signal and then amplified by electronic amplifier and again converted to optical signal. On the other hand, optical amplifiers can amplify the optical signal directly without converting to electrical and provides better efficiency and performance. After the development of optical amplifiers, there have been considerable developments in point to point optical transmission with wavelength division multiplexing with cascaded optical amplifiers. Further development in optical components was made in the development of optical add-drop multiplexers (OADM), optical cross-connect (OXC) and optical routers as shown in Fig. A.3.

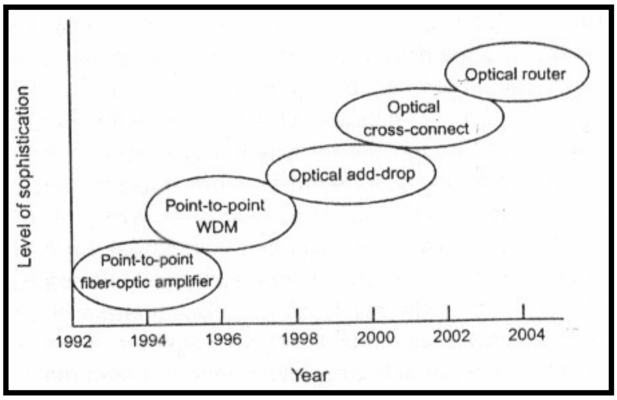


Fig. A.3: Development of WDM optical components

The development in the WDM components makes it possible to develop WDM networks to meet up the growing demand of gigabit internet.

APPENDIX - B

Theoretical approach to determine Q-factor and BER

A basic optical fiber communication system consists of an optical transmitter (modulator, Channel coupler and optical source e.g. LED, LASER), a Transmission channel (optical fiber), and a optical receiver (optical amplifier, electronic processing circuitry and optical detector e.g. PIN, APD).

BER analysis for intensity modulation (ID) and direct detection (DD)

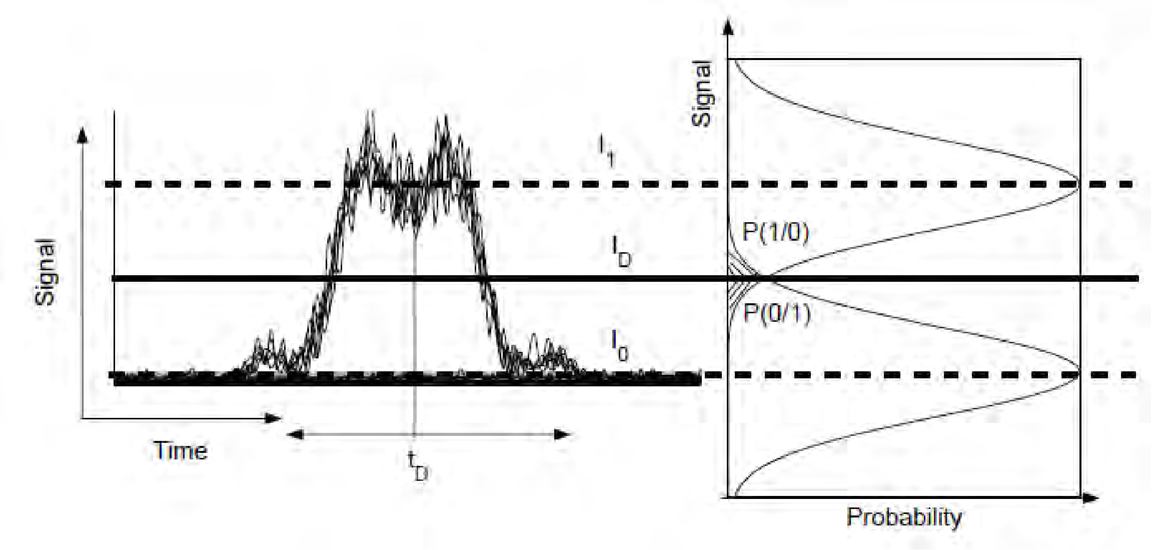


Fig. B.1: Bit error probabilities

Bit Error Rate (BER):

Optical receivers convert incident optical power into electric current through a photodiode. Among a group of optical receivers, a receiver is said to be more sensitive if it achievers the same performance with less optical power incident on it. The communications system performance is characterized by a quantity called the bit error rate (BER) which is defined as the average probability of incorrect bit identification of a bit by the decision circuit of the receiver. For example, a BER of 2×10^{-6} would correspond to on average 2 errors per million bits. A commonly used criterion for digital optical receivers requires BER $\leq 1 \times 10^{-9}$. It is important for the signal to have minimum distortions in order to avoid a high BER at the receiver. This means that although the combined effects of GVD, SPM and IRS cannot be eliminated they need to be reduced so that the pulse can propagate with minimum distortions. Also the inevitable presence of amplifier noises can also cause pulse distortions and hence cause system degradation. In order to assess the system performance one needs to know how to calculate the BER of the system at the receiver end. In this chapter we calculate the BER of the system at the receiver in the presence of amplifier noises.

Fig. B.1 shows schematically the fluctuating signal received by the decision circuit, which samples it at the decision instant t_D determined through clock recovery. The sampled value I fluctuates from bit to bit around an average value I_1 or I_0, depending on whether the bit corresponds to 1 or 0 in the bit stream. The decision circuit compares the samples value with the threshold value I_D and calls it bit 1 if $I > I_D$ or bit 0 if $I < I_D$. An error occurs if $I < I_D$ for bit 1 or if $I > I_D$ for bit 0 due to amplifier noises that add into the signal in the system. Both sources of errors can be included by defining the error probability as

$$\mathrm{BER} = p(1)P(1/0) + p(0)P(0/1), \tag{B.1}$$

where, p(1) and p(0) are the probabilities of receiving bits 1 and 0, respectively. P(0/1) is the probability of deciding 0 when 1 is received and P(1/0) is the probability of deciding 1 when 0 is received. Since 1 and 0 bits are equally likely to occur, p(1) = p(0) = ½, and the BER becomes

$$BER = \frac{1}{2}\{P(1/0) + P(0/1)\} \tag{B.2}$$

Fig. B.1 shows how P(0/1) and P(1/0) depend on the probability density function p(I) of the sampled value I. The functional form of p(I) depends on the statistics of noise sources responsible for current fluctuations. Assuming a Gaussian noise profile, one can write the functional form of P(0/1) and P(1/0) as

$$P(0/1) = \frac{1}{\sigma_1\sqrt{2\pi}}\int_{-\alpha}^{I_D} \exp\left(-\frac{(I - I_1)^2}{2\sigma_1{}^2}\right)dI \tag{B.3}$$

$$P(1/0) = \frac{1}{\sigma_0\sqrt{2\pi}}\int_{I_D}^{\alpha} \exp\left(-\frac{(I - I_0)^2}{2\sigma_0{}^2}\right)dI \tag{B.4}$$

where, $\sigma_1{}^2$ and $\sigma_0{}^2$ are the corresponding variance. From the definition of the complimentary error function we have

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^{\alpha} \exp(-x^2)dx \tag{B.5}$$

Using Eq. (B.5) in Eqs. (B.3) and (B.4) we get

$$P(0/1) = \frac{1}{2} erfc\left(\frac{I_1 - I_D}{\sqrt{2}\sigma_1} \right) \tag{B.6}$$

$$P(1/0) = \frac{1}{2} erfc\left(\frac{I_D - I_0}{\sqrt{2}\sigma_0} \right) \tag{B.7}$$

Using Eqs. (B.6) and (B.7) in Eq. (B.2) we can write the BER as

$$BER = \frac{1}{4}\left[erfc\left(\frac{I_1 - I_D}{\sqrt{2}\sigma_1} \right) + erfc\left(\frac{I_D - I_0}{\sqrt{2}\sigma_0} \right) \right] \tag{B.8}$$

Eq. (B.8) shows that the BER depends on the decision threshold $I_{D.}$

Q-factor:

In practice, I_D is optimized to minimize the BER. Hence we minimize BER with respect to I_D using

$$\frac{d}{dx} erfc\left| f(x) \right| = \frac{2}{\sqrt{\pi}} e^{-f^2} - \frac{df}{dx} \tag{B.9}$$

and obtain

$$\frac{(I_1 - I_D)^2}{\sigma_1{}^2} = \frac{(I_D - I_0)^2}{\sigma_0{}^2} + \ln\left(\frac{\sigma_1}{\sigma_0} \right) \tag{B.10}$$

For most practical cases, the last term is negligible and hence we get

$$\frac{(I_1 - I_D)}{\sigma_1} = \frac{(I_D - I_0)}{\sigma_0} \tag{B.11}$$

Hence, we can find that the minimum occurs when

$$I_D = \frac{\sigma_0 I_1 + \sigma_1 I_0}{\sigma_0 + \sigma_1} \tag{B.12}$$

when, $\sigma_1 = \sigma_0, I_D = {(I_1 + I_0)}/{2}$, which corresponds to setting the decision threshold in the middle. The BER is then given by

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \tag{B.13}$$

where, the factor Q is given by

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \tag{B.14}$$

The Q factor is thus a dimensionless factor and is related to the BER as shown in Eq. (B.13). Fig. B.2 shows how BER varies with Q factor.

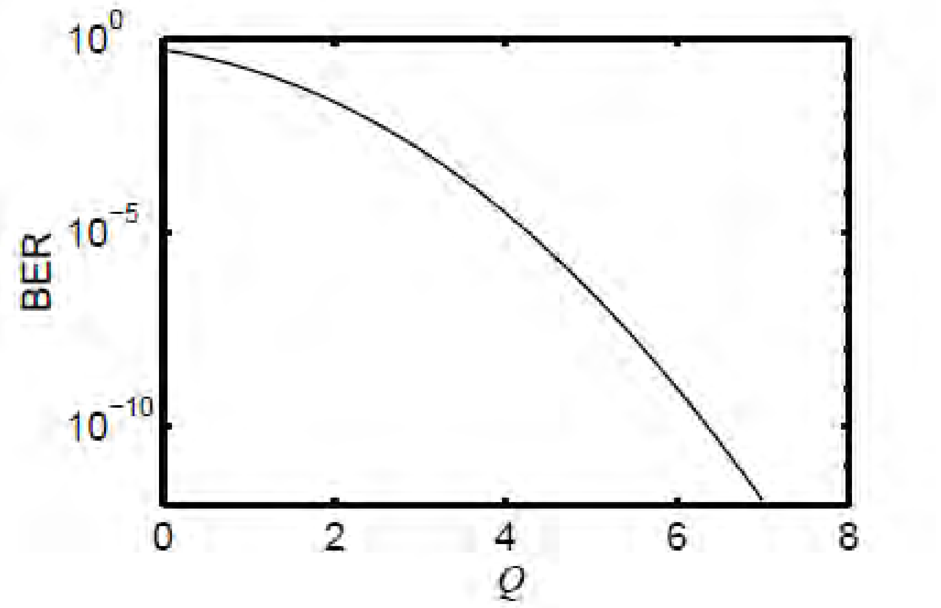


Fig. B.2: BER versus Q-factor

Measurement of System Performance

After power budget and rise time budget, the system performance requirements (for thermal noise limited systems), SNR and BER should be verified according to following equations:

$$\frac{S}{N} = \left(\frac{\eta e P_r M}{hf}\right)^2 \times \frac{R_L}{4kTB_e} = \frac{P_s}{P_n} \tag{B.15}$$

and

$$BER = 0.5 erfc\left(0.354\sqrt{{S}/{N}}\right) \tag{B.16}$$

APPENDIX - C

Data for Simulation Results

Table C.1 : Simulation results of the 10 Gbps transmission link using EDFA alone. (Noise Figure varies with 2 to 5 dB)

Link	Distance	Parameter	NF=2	NF=3	NF=4	NF=5
Dhk-Cml	103 Km	BER	0.78E-06	0.54E-06	0.13E-05	0.59E-06
		Q-Value	13.6	13.7	13.4	13.7
Dhk-Feni	166 Km	BER	0.13E-01	0.13E-01	0.13E-01	0.13E-01
		Q-Value	6.8	6.8	6.8	6.8
Dhk-Ctg	267 Km	BER	0.22E-01	0.22E-01	0.22E-01	0.22E-01
		Q-Value	6.0	6.0	6.0	6.0
Dhk-Chr	367 Km	BER	0.22E-01	0.22E-01	0.22E-01	0.22E-01
		Q-Value	6.0	6.0	6.0	6.0
Dhk-Cxb	437 Km	BER	0.22E-01	0.22E-01	0.22E-01	0.22E-01
		Q-Value	6.0	6.0	6.0	6.0

Table C.2 : Simulation results of the 10 Gbps transmission link using EDFA alone. (Noise Figure varies with 6 to 9 dB)

Link	Distance	Parameter	NF=6	NF=7	NF=8	NF=9
Dhk-Cml	103 Km	BER	0.81E-06	0.14E-05	0.30E-06	0.28E-06
		Q-Value	13.6	13.4	13.9	13.9
Dhk-Feni	166 Km	BER	0.13E-01	0.13E-01	0.13E-01	0.12E-01
		Q-Value	6.9	6.9	6.8	6.9
Dhk-Ctg	267 Km	BER	0.22E-01	0.22E-01	0.22E-01	0.22E-01
		Q-Value	6.0	6.0	6.0	6.0
Dhk-Chr	367 Km	BER	0.22E-01	0.22E-01	0.22E-01	0.22E-01
		Q-Value	6.0	6.0	6.0	6.0
Dhk-Cxb	437 Km	BER	0.22E-01	0.22E-01	0.22E-01	0.22E-01
		Q-Value	6.0	6.0	6.0	6.0

Table C.3: Simulation Results of 10 Gbps Transmission Link with DCF and EDFA (Noise Figure varies with 2 to 5 dB)

Link	Distance	Parameter	NF=2	NF=3	NF=4	NF=5
Dhk-Cml	103 Km	BER	0.28E-12	0.41E-13	0.23E-09	0.44E-09
		Q-Value	17.1	17.4	15.8	15.7
Dhk-Feni	166 Km	BER	0.58E-08	0.57E-07	0.52E-06	0.53E-05
		Q-Value	15.1	14.4	13.7	12.8
Dhk-Ctg	267 Km	BER	0.99E-03	0.34E-02	0.10E-01	0.11E-01
		Q-Value	9.7	8.6	7.2	7.1
Dhk-Chr	367 Km	BER	0.98E-04	0.89E-05	0.31E-03	0.14E-03
		Q-Value	11.4	12.6	10.6	11.1
Dhk-Cxb	437 Km	BER	0.50E-05	0.29E-05	0.24E-03	0.23E-03
		Q-Value	12.8	13.1	10.8	10.8

Table C.4: Simulation Results of 10 Gbps Transmission Link with DCF and EDFA (Noise Figure varies with 6 to 9 dB)

Link	Distance	Parameter	NF=6	NF=7	NF=8	NF=9
Dhk-Cml	103 Km	BER	0.50E-09	0.38E-06	0.14E-04	0.51E-04
		Q-Value	15.7	13.8	12.4	11.7
Dhk-Feni	166 Km	BER	0.20E-03	0.80E-03	0.10E-02	0.83E-02
		Q-Value	10.9	9.9	9.7	7.5
Dhk-Ctg	267 Km	BER	0.14E-01	0.22E-01	0.22E-01	0.22E-01
		Q-Value	6.7	6.0	6.0	6.0
Dhk-Chr	367 Km	BER	0.83E-03	0.82E-02	0.52E-02	0.18E-01
		Q-Value	9.9	7.6	8.1	6.4
Dhk-Cxb	437 Km	BER	0.48E-02	0.64E-02	0.61E-02	0.20E-01
		Q-Value	8.2	7.9	7.9	6.1

Table C.5: Simulation Results of 10 Gbps Transmission Link with DCF and SOA (Noise Figure varies with 2 to 5 dB)

Link	Distance	Parameter	NF=2	NF=3	NF=4	NF=5
Dhk-Cml	103 Km	BER	0.99E-40	0.99E-40	0.99E-40	0.99E-40
		Q-Value	22.4	22.4	22.4	22.4
Dhk-Feni	166 Km	BER	0.39E-24	0.67E-21	0.29E-15	0.65E-13
		Q-Value	20.2	19.5	18.1	17.3
Dhk-Ctg	267 Km	BER	0.93E-10	0.17E-09	0.53E-06	0.12E-05
		Q-Value	16.0	15.9	13.7	13.4
Dhk-Chr	367 Km	BER	0.18E-07	0.82E-09	0.16E-05	0.14E-05
		Q-Value	14.8	15.6	13.3	13.4
Dhk-Cxb	437 Km	BER	0.81E-13	0.43E-13	0.11E-12	0.88E-14
		Q-Value	17.3	17.4	17.3	17.6

Table C.6: Simulation Results of 10 Gbps Transmission Link with DCF and SOA (Noise Figure varies with 2 to 5 dB)

Link	Distance	Parameter	NF=6	NF=7	NF=8	NF=9
Dhk-Cml	103 Km	BER	0.99E-40	0.99E-40	0.11E-36	0.50E-25
		Q-Value	22.4	22.4	22.1	20.4
Dhk-Feni	166 Km	BER	0.21E-11	0.10E-12	0.29E-07	0.13E-07
		Q-Value	16.8	17.3	14.6	14.8
Dhk-Ctg	267 Km	BER	0.88E-05	0.85E-04	0.44E-03	0.56E-03
		Q-Value	12.6	11.4	10.4	10.2
Dhk-Chr	367 Km	BER	0.30E-08	0.50E-07	0.12E-04	0.29E-05
		Q-Value	15.2	14.5	12.5	13.1
Dhk-Cxb	437 Km	BER	0.72E-09	0.17E-09	0.77E-08	0.15E-06
		Q-Value	15.6	15.9	15.0	14.1