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Study and Simulation of DWDM Star Topology Network

Presented by:

- **BOUCHAFA Safia**
- **KHODJA Khalida**

Supervisor:

A. ZITOUNI

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Dedication

This work is dedicated to every individual who believed in us and helped us walking through our path to succeed in this academic journey, which was a long one filled with hard work and perseverance.

We would like to thank our parent who took a major part in this course, even though thank you isn't enough to repay their favor.

We would also like to send our greatest love to our sisters and brothers, friends and family members who were also a source for our aspirations ambitions.

Khalida & Safia

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Abstract

Nowadays, optical networks employing Dense Wavelength Division Multiplexing (DWDM) are the adopted technique used in modern communication networks that can meet the ever-increasing demand for bandwidth of the end users. The development of nodal elements, such as Optical Cross-Connects (OXC) for DWDM networks, has led to huge possible network architectures for the optical layer.

In this project, we study the effect of the input power, transmission speed, pre- and post-compensation techniques on the performance of an eight channel DWDM star topology operating at wavelength 1550 nm and consisting of a central node to which 64 other nodes are connected. OptiSystem 7.0 is used for building the overall system and carrying out simulations. The performance analysis is based on eye diagrams, Q Factor and simulated Bit Error Rate (BER).

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List of Abbreviations

AON	Active Optical Networks
APD	Avalanche Photodetector Diode
ATB	Access Terminal Box
BER	Bit Error Rate
CWDM	Coarse Wavelength Division Multiplexing
DCF	Dispersion Compensating Fiber
DMUX	Demultiplxer
DWDM	Dense Wavelength Division Multiplexing
FAT	Fiber Access Terminal
FBG	Fiber Bragg Grating
FDT	Fiber Distribution Frames
FEC	Forward Error Correction
FWM	Four Wave Mixing
FTTH	Fiber To the Home
GPON	Gigabit Passive Optical Networks
ITU-T	International Telecommunication Union – Telecommunications Standardization Sector
LAN	Local Area Networks
LASER	Light Amplification by Stimulated Emission of Radiation
LED	Light Emitting Diode
LPF	Low Pass Filter
MMFs	Multimode Fibers
MUX	Multiplexer
MZM	Mach-Zehnder modulator
NRZ	Non-Return-to-Zero
OADM	Optical Add/Drop Multiplexers
OC	Optical Carrier
Och	Optical Channel
ODU	Optical Data Unit
O-E-O	Optical-Electrical-Optical
OLT	Optical Line Terminal
OMS	Optical Multiplex Section

List of Abbreviations

ONT	Optical Network Terminal
OPU	Optical Payload Unit
OSC	Optical Supervising Channel
OSNR	Optical Signal-to-Noise Ratio
OTN	Open Transport Network
OTS	Optical Transmission Section
OTU	Optical Transport Unit
OXC	Optical Cross Connect
PIN	Positive Intrinsic Negative
PMD	Polarization Mode Dispersion
PON	Passive Optical Networks
PRBS	Pseudo Random Binary Sequence
ROF	Radio Over Fiber
SBS	Stimulated Brillouin Scattering
SDH	Synchronous Digital Hierarchy
SMFs	Single Mode Fibers
SOA	Semiconductor Optical Amplifier
SONET	Synchronous Optical Network
SPM	Self Phase Modulation
SRS	Stimulated Raman Scattering
STM	Synchronous Transport Module
STS	Synchronous Transport Signal
TDM	Time Division Multipluxing
VCSEL	Vertical Cavity Surface Emitting Laser
WAN	Wide Area Networks
WDM	Wavelength Division Multiplexing
XPM	Cross Phase Modulation

Introduction

In this digital era, the communication demand has increased from previous eras due to introduction of new communication techniques. As we can see, there is increase in clients day by day, so we need huge bandwidth and high speed networks to deliver good quality of service to clients. Optical fiber communication is one of the major communication systems in modern era. It is seen as one of the most reliable, fastest and secure technologies that meet up the above challenges.

The rapid growth in demand for high-capacity telecommunication bandwidth and the speed limitation of single-wavelength links has resulted in an extraordinary increase in the use of DWDM in advanced light wave networks. DWDM is a method of transmitting data from different sources over the same fiber optic link at the same time whereby each data channel is carried on its own unique wavelength [24]. DWDM technology can maximize the capacity of the existing fiber optic network without adding additional fibers. At the destination, wavelengths are spatially separated to different receiver locations [9]. However, dispersion and nonlinearities are the major limiting factors in high-speed optical DWDM network. Therefore, some amplification and dispersion compensation scheme should be used to achieve the enormous benefits of DWDM system and increase the efficiency of the network.

In this project, a DWDM star topology is studied and simulated. OptiSystem 7.0 is used for building the proposed system and carrying out simulations. This report is organized in four main chapters:

The **first chapter** introduces optical fiber communication systems, their basic components and optical fiber technology. It describes also the structure of an optical cable, its types and characteristics.The **second Chapter** covers DWDM technology and its importance in nowadays application. Besides, it provides an overview of the different components needed to build such networks.The **third chapter** deals with DWDM network architecture and topologies. Specially presents one of the new technology emerged in recent years, which is passive optical network solution for Fiber-To-The-Home (FTTH) access network applications. The **fourth chapter** is devoted to the design and simulation of DWDM star transmission system of an 8 channel operating at different bit rates in the range of 2.5 Gbps up to 80 Gbps, by applying various input powers and dispersion compensation techniques. The obtained results are used to examine the system performance. Finally, we will end up with a **conclusion** that summarizes the outcome, states briefly the achievements of this project and discusses some recommendations for future work in this topic.

Chapter I

Optical Fiber Communication Systems

I.1 Introduction

The increasing demand of internet services and the growth of data traffic need high capacity networks with a huge bandwidth. Optical fiber communication is the key technology to realize these high capacity network infrastructures, which are required to “keep pace” with this global trend of exponential increase in traffic volume. This chapter deals with the basic elements of an optical fiber system. At the beginning, a general overview of a simple optical network is given. After that, the main subsystems of an optical transmitter are presented, the structure of an optical cable and how light is transmitted through it is described. Next, the phenomena of loss, dispersion and fiber nonlinearities, which play a major role in the design of transmission systems are discussed. This chapter is concluded by presenting the different parts of an optical receiver.

I.2 General Overview of Optical Fiber Communication Systems

A fiber Optic Communication System that uses light wave technology to transmit data over a fiber by changing electric signals into light becomes major building block in any telecommunication infrastructure due to its huge advantages.

Mainly an optical fiber system is composed of three basic components as depicted in Figure.I.1:

- Optical Transmitter
- Optical Cable
- Optical Receiver

In addition, accessories like connectors, switches, couplers, multiplexing devices, amplifiers and splices are also essential elements in this communication system.

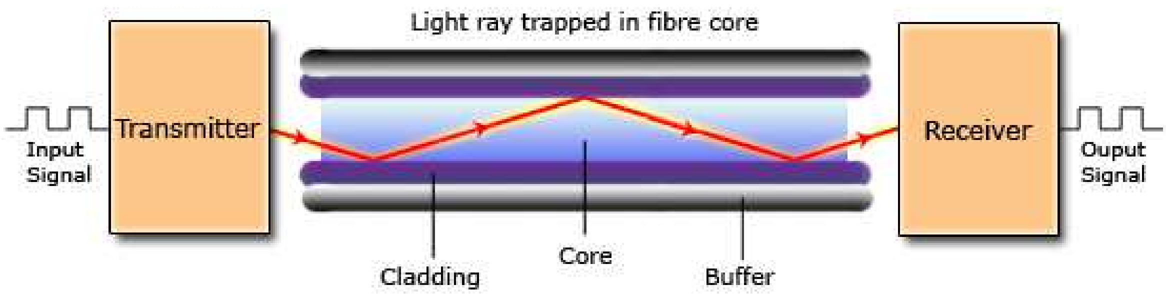


Figure I. 1: Generic Optical Communication System [31].

I.2.1 Optical Transmitter

The role of an optical transmitter is to convert the electrical signal to optical form and launch the resulting optical signal into the optical fiber. Figure I.2 shows the block diagram of an optical transmitter.

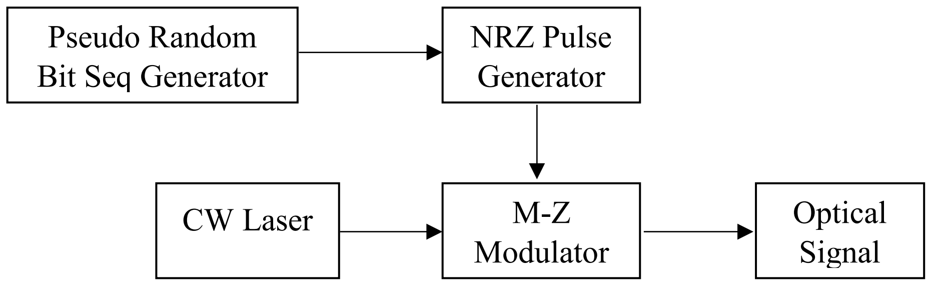


Figure I. 2: Optical Transmitter Structure [22].

The transmitter consists of four sections. The first section is data source, which produces a Pseudo Random Binary Sequence (PRBS) that represents the information to be transmitted. The second section is Non-Return-to-Zero (NRZ) pulse generator. It converts the binary data into electrical pulses. For more details about this encoding technique see Appendix-A-.

The third section of an optical transmitter is a light source that might be a Light Emitting Diode (LED), a Vertical Cavity Surface Emitting Laser (VCSEL), or a Light Amplification by Stimulated Emission of Radiation (LASER) diode. These sources use wavelengths in the infrared band, specifically 850nm, 1300nm and 1550nm.

The last section is the Mach-Zehnder Modulator (MZM). It is an external modulator used to vary the intensity of the light source from the laser according to the output of the NRZ pulse generator.

I.2.2 Optical Cable

An optical fiber is a thin, filament cylindrical dielectric waveguide in which information is transmitted through a glass or plastic in the form of light. It consists of three basic concentric layers, which are illustrated in Figure I.3.

- Core: It is a cylinder made of silica or doped silica that runs all along the fiber cable's length and offers protection by cladding. It is the light transmitting region of the fiber. The diameter of the core depends on the used application; however, the larger the core, the more light the cable can carry.

- Cladding: The outer optical material that surrounds the fiber core, also made of silica but with a slightly lower refractive index (usually about 1% lower). This creates an optical waveguide, which confines the light in the core by total internal reflection at the core-cladding interface.
- Coating: The first non-optical layer around the cladding. Usually, the coating consists of one or more polymer layers that protect the core and cladding from the fracture and environmental damage.

Optical cable may then be covered with a buffer that protects the structure from damages and a plastic jacket bundled with other fibers to make up a larger cable.

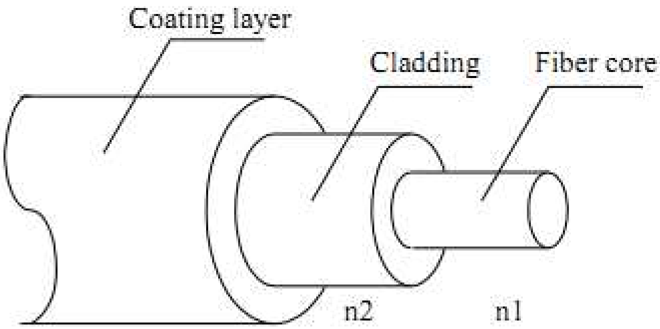


Figure I. 3: Optical Fiber Structure [26].

I.2.2.1 Transmission Principle

The propagation of light in optical fibers is based on the phenomenon of total internal reflection, which is shown in Figure I.4 below.

When a beam of light passes from the core that has higher refractive index than the cladding it strikes the surface at less than the critical angle and reflects. The difference between the refractive indices of the two materials causes most of the transmitted light to bounce off the cladding and stay within the core. The critical angle requirement is met by controlling the angle at which the light is injected into the fiber [9].

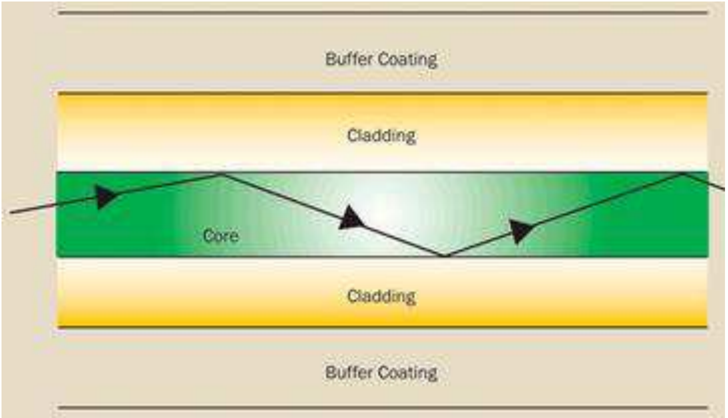


Figure I. 4: Principle of Total Internal Reflection [32].

I.2.2.2 Fiber Types

There are two general categories of optical fiber that are in use today, single-mode fiber and multimode fiber, these are represented in Figure I.5.

a. Single Mode Fibers

In Single Mode Fibers (SMFs), the core is much smaller so, the fiber can support only one mode that travels straight through the fiber with no reflections from the core-cladding interface.

b. Multimode Fibers

Multimode Fibers (MMFs), has a larger core than single-mode fiber. As a result, the beam of light propagates in the fiber by following multi-paths called modes. Each mode has a slightly different reflection angle.

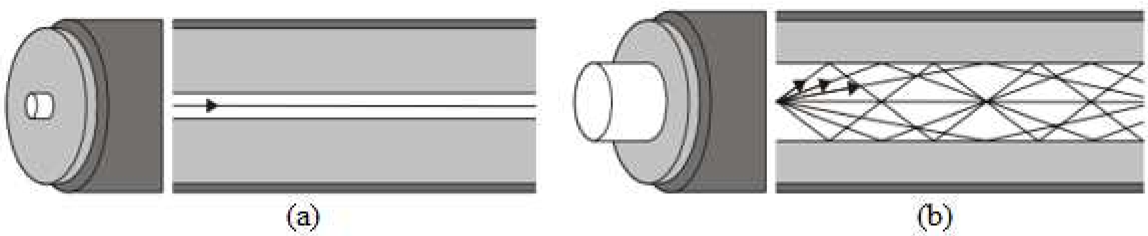


Figure I. 5: The Two Principal Types of Fibers

(a) Single-Mode Fiber (b) Multimode Fiber.

I.2.2.3 Fiber Losses

The optical signal faces several degradation phenomena during transmission that limit its performance, such as attenuation, dispersion and the nonlinear effects.

a. Attenuation

Attenuation, also known as transmission loss, is the decrease in magnitude of the light beam intensity with respect to distance travelled through a transmission medium. Mathematically, it is defined as the ratio of the optical power output to the optical power input in the fiber, of length L. Attenuation consists of three types: absorption, scattering and bending. The attenuation coefficient α is wavelength dependent and directly proportional to the length of the cable. It represents the loss in dB per kilometer of fiber as shown in equation (I.1)

$$\alpha(\mathrm{dB/km}) = -\frac{10}{\mathrm{L}} Log_{10}\left(\frac{\mathrm{P_{out}}}{\mathrm{P_{in}}}\right) \tag{I.1}$$

Where L, P_{in}, and P_{out} are the total length of the fiber, input power and output power respectively.

❖ Absorption Loss

Material absorption is related to the material composition and the fabrication process for the fiber, which results in the dissipation of some of the transmitted optical power as heat in the waveguide. The absorption of the light may be intrinsic (caused by the interaction with one or more of the major components of the glass) or extrinsic (caused by impurities within the glass).

- **Intrinsic Absorption**

Is very low compared to other types of losses, the main cause in infrared region is the characteristic vibration frequency of atomic bonds. In silica glass, absorption is caused by the vibration of silicon oxygen bond. The interaction between the vibrating bond and the electromagnetic field of the optical signal (photons and electrons) will transfer the light energy from electromagnetic field to the bond causing attenuation.

- **Extrinsic Absorption**

Is much more significant and it results from the presence of impurities introduced into the glass during the manufacturing processes like iron, nickel, chromium and OH^- (i.e. from water), which remains a severe obstacle for modern manufacturing techniques to reduce the impact of extrinsic absorption.

❖ **Scattering Loss**

Scattering loss in glass arise from microscopic variation in the material density, compositional fluctuation, structural inhomogeneities and manufacturing defects [3].The glass contains metallic ions that acts like small mirrors. When light is traveling down the fiber it collides and reflects off this metallic ions and get reflected either back to the source or out of the core of the fiber. It has two type: Rayleigh and Mie scattering (Figure I.6).

- **Rayleigh Scattering**

It results from inhomogeneities of a random particles much smaller than the wavelength of the radiation. These particles are less than $1/10^{th}$ of the incident light wavelength, the scattered light caries the same energy (elastic scattering) to the incident light and is angle-independent.

- **Mie Scattering**

It may occur at compositional fluctuation and structural inhomogeneities which are comparable in size (> λ /10) with the guided wavelength. This results from the non-perfect cylindrical structure of the waveguide .The scattered light is unequal in energy (inelastic scattering) to the incident light and is angle-dependent where the energy is most intense towards the direction of the incident light.

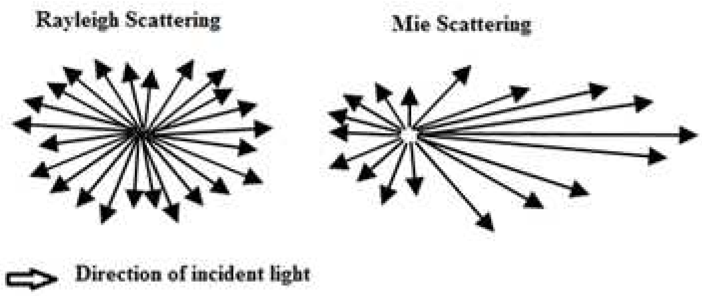


Figure I. 6: Difference between Rayleigh and Mie Scattering [37].

❖ **Bending Loss**

There exist two main types of bending (Figure I.7), Micro and Macro Bending.

- **Macro Bending**

As the radius of curvature decreases, the loss increases exponentially until at a certain critical radius of curvature loss becomes observable. Since any bound core mode has an evanescent field tail in the cladding moving along with the field in the core, for the lowest order mode, when a fiber is bent, the field tail on the far side of the center of curvature must move faster to keep up with the field in the core. However, at a certain critical distance x_c, from the center of the fiber; the field tail would have to move faster than the speed of light to keep up with the core field. Since this is not possible the optical energy in the field tail beyond x_c will radiates away.

- **Micro Bending**

Micro bends are repetitive small scale fluctuations in the radius of curvature of the fiber axis. They are caused either by non-uniformities in the manufacturing cycles of the fiber or by non-uniform lateral pressures created during the cabling of the fiber. These micro curvatures cause repetitive coupling of energy between the guided modes and non-guided modes in the fiber [3].

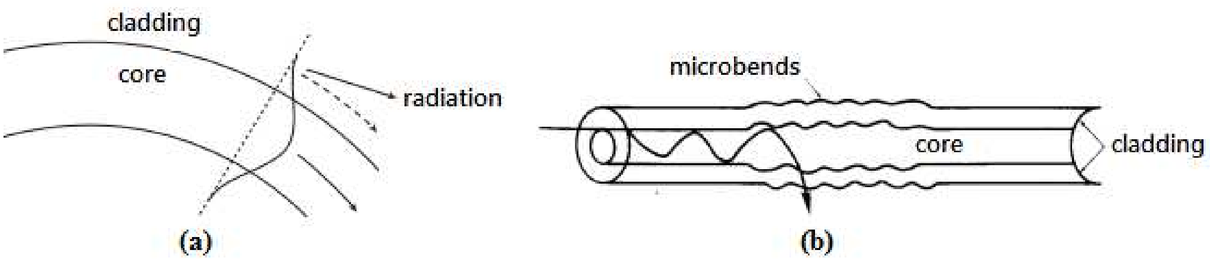


Figure I. 7: Types of Bending (a) Macro Bending [6] (b) Micro Bending [3].

b. Dispersion

Dispersion is the broadening of the input pulse in time as it propagates along the fiber. When light pulses are lunched to the fiber different spectral components of the pulse disperse during propagation and do not arrive simultaneously at the end and eventually the information will be lost.

❖ **Intra-Modal Dispersion**

Intra-modal, also known as chromatic dispersion may occur in all types of optical fibers (SMF and MMF). It refers to the different spectral components of light pulse traveling at different velocities with a propagation delay, this delay is caused by the properties of the waveguide (material dispersion) and by the guideness effect of the waveguide (waveguide dispersion)[6].

- **Material Dispersion**

Material dispersion is generated due to the frequency dependence of the refractive index of glass [4].When a group of wavelength is lunched into the fiber, different frequency components will travel at different speeds in the glass leading to pulse spreading [8].

- **Waveguide Dispersion**

The refractive index of a mode lies between the refractive indices of cladding /core and the actual value of the effective index between these two limits depends on the proportion of power that is contained in the cladding /core. If most of the power is contained in the core, the effective index is closer to the core refractive index; if most of it propagates in the cladding, the effective index is closer to the cladding refractive index. More accurately, the longer the wavelength, the more power in the cladding, the higher the spread of light.

❖ **Intermodal Dispersion**

The intermodal dispersion is due to the difference in propagation delay (velocity) of various modes inside a fiber, obviously the intermodal dispersion takes place in a multi-mode fiber.

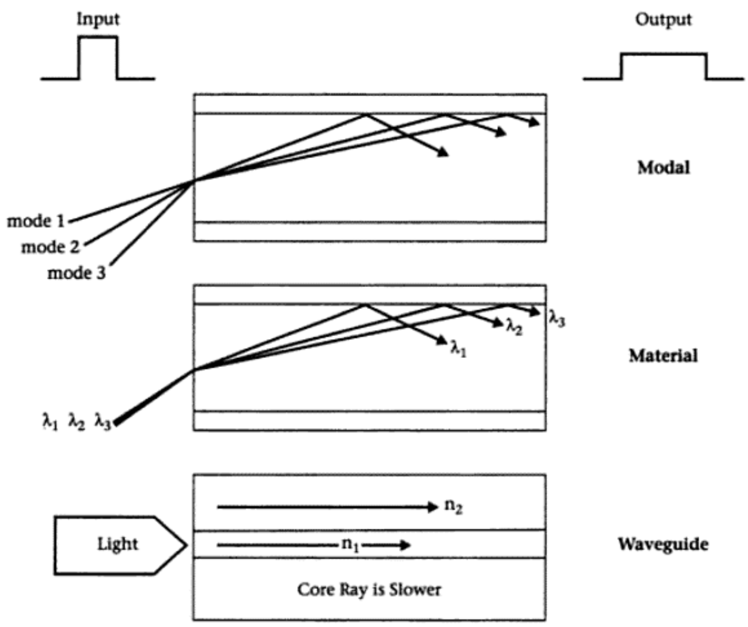


Figure I. 8: Intra-Modal and Intermodal Dispersion [38].

❖ **Polarization Mode Dispersion**

Fibers are slightly birefringent, they consist of two orthogonally polarized modes that have different propagation constants. In reality, fibers are not perfectly circularly symmetric, so the light energy of a pulse propagating in a fiber will usually be split between these two modes, this birefringence gives rise to pulse spreading. This phenomenon is called Polarization-Mode Dispersion (PMD).

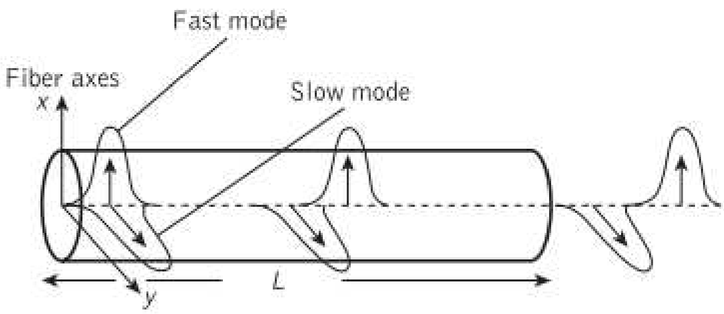


Figure I. 9: Polarizaion Mode Disperssion [6].

c. Nonlinear Effects

There are two categories of nonlinear effects. The first arises due to the interaction of light waves with phonons (molecular vibrations) in the silica medium. The second set of nonlinear effects arises due to the dependence of the refractive index on the intensity of the applied electric field, which in turn is proportional to the square of the field amplitude [4].

❖ First Category

The two main effects in this category are Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS). Both of them can be understood as scattering of a photon to a lower energy photon such that the energy difference appears in the form of a phonon. The main difference between the two is that optical phonons participate in Raman scattering, whereas acoustic phonons participate in Brillouin scattering [1]. Both scattering processes result in a loss of power at the incident frequency. However, SBS can produce gain in the opposite direction propagation. Thus, it depletes the transmitted signal as well as generates a potentially strong signal back toward the transmitter [4]. Whereas SRS causes power to be transferred from the lower-wavelength channels to the higher wavelength as shown in the Figure I.10

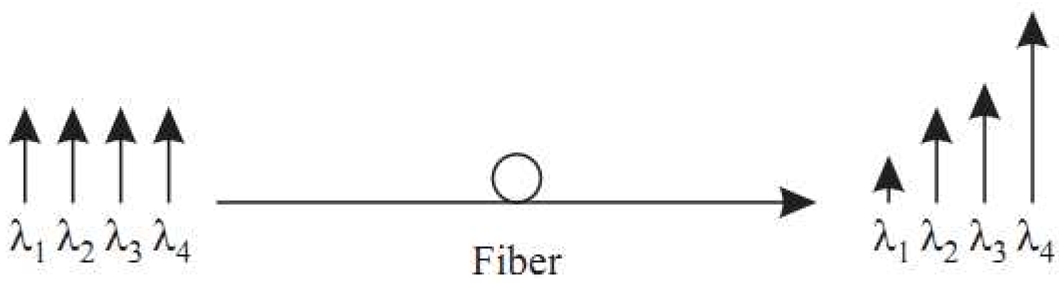


Figure I. 10: Simulated Raman Scattering [4].

❖ **Second Category**

The most important nonlinear effects in this category are Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM) and Four-Wave Mixing (FWM).

- **Self-Phase Modulation (SPM)**: The refractive index depends on the intensity of light. This dependence causes an induced phase shift that is proportional to the intensity of the pulse. Thus, different parts of the pulse undergo different phase shifts, which gives rise to the chirp of the pulses. Pulse chirping in turn enhances the pulse-broadening effects of chromatic dispersion. This chirping effect is proportional to the transmitted signal power so that SPM effects are more pronounced in systems using high transmitted powers [7].

- **Cross-Phase Modulation (XPM)**: It is similar to SPM except that it involves different wavelengths or polarizations. In this case, variations in intensity of one pulse will modulate the refractive index of the fiber, which causes phase modulation of the overlapping pulses. As with SPM, this phase modulation translates into frequency modulation, which broadens the pulse spectrum. Thus, XPM is exhibited as a crosstalk mechanism between channels. Moreover, the strength of XPM increases with the number of channels and it also becomes stronger as the channel spacing is made smaller as in DWDM [6].

- **Four-Wave Mixing (FWM)**: FWM is a third order nonlinear effect caused by dependence of refractive index on the intensity of the optical power; it is most considerable in closely spacing WDM systems. The interaction between three wavelengths ω_1, ω_2, and ω_3 generates new wavelengths at frequencies $\omega_i \pm\omega_j \pm\omega_k$ which may lie on or very close to one of the individual channels resulting a cross talk [4].

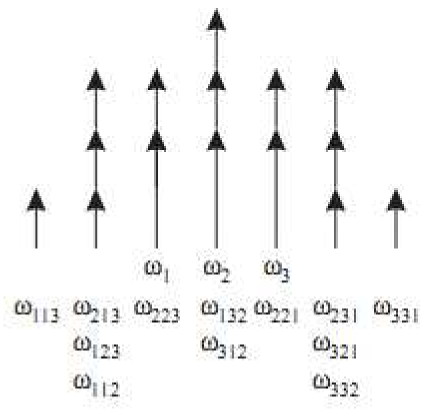


Figure I. 11: Four Wavelength Mixing [4].

I.2.2 Optical Receiver

The function of the optical receiver is to detect the incoming optical power and extract from it the transmitted signal. The first receiver element is a Positive Intrinsic Negative diode (PIN) or Avalanche Photodetector Diode (APD), which produces an electrical current proportional to the received power level. Since the electrical current is typically very weak, a font end amplifier is added to boot it to a level that can be used by the next element. After being amplified the signal passes through a Low Pass Filter (LPF) to reduce the noise that it outside the signal bandwidth [41].At the end, an integrated signal processing circuit is added to analyze the delivered data.

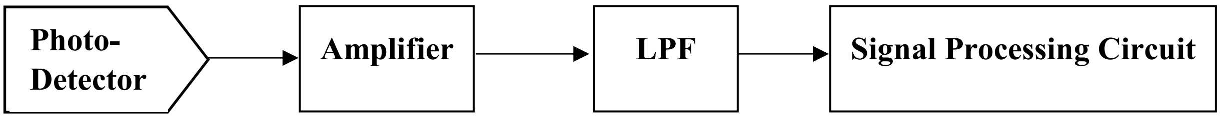


Figure I. 12: Optical Receiver.

I.3 Conclusion

In this chapter, an optical transmission link with its different components are presented including the various impairments effecting the signal flow in fibers.

New technologies have improved optical networking from conventional multimode to the more exotic single mode fiber; this caused a steep increase in communication data rates. Further, multiplexing and demultiplexing techniques will be deployed in various forms of communication systems to give birth to new transmission technologies like Synchronous Optical Network /Synchronous Digital Hierarchy (SONET/SDH) and Wavelength Division Multiplexing (WDM).This last will be discussed with more details in the next chapter.

Chapter II

DWDM Systems

II.1 Introduction

So far, the previous chapter described the three components of an optical fiber system and the main characteristics of an optical cable. In this chapter, the focus is on the physical layer of WDM optical networks and some of the components needed for their implementation. An overview of the evolution of the different technologies like SONET/SDH, WDM and Open Transport Network (OTN) are provided. Then, a description of the basic components involved in WDM technology is given. Finally, this chapter is concluded by introducing some elementary mathematical relations of Q-factor and BER that affect the system design.

II.2 Evolution of Optical Transport Technologies

In this section, the growth of the transmission technologies from SDH/SONET to WDM and OTN is discussed including the main difference between them.

II.2.1 Synchronous Digital Hierarchy and Synchronous Optical Network

Synchronous Digital Hierarchy (SDH) is the current transmission and multiplexing standard for high-speed signals within the carrier infrastructure in Europe. While a closely related standard, Synchronous Optical Network (SONET) has been adopted in North America [4]. The information transmitted by SONET/SDH is organized into frames, transmitted continuously one after the other. Each frame consists of a collection of overhead fields and a payload. SONET/SDH equipment construct these frames in the electrical domain and then transmit them out optically. At the receiving end, the optical signal is converted back into electrical to process the frames [5].

The electrical side of the SONET signal is known as the Synchronous Transport Signal (STS). Each synchronous transport signal level-1 (STS-1) has bit rate of 51.84 Mb/s. Lower-rate payloads are mapped into STS-1s and higher-rate signals (STS-N) are obtained by interleaving the bytes from N frame-aligned STS-1s where N = 1, 3, 12, 24, 48 and 192. The transmission rate of STS-N is N * 51.84 Mbps [4]. Whereas, the electrical side of the SDH is known as the Synchronous Transport Module (STM), each STM-1 has a bit rate of 155.52 Mb/s. The lower-rate payloads are mapped into an STM-1, and higher-rate signals are obtained by multiplexing N STM-1 signals to form an STM-N signal, where N = 1, 4, 16, and 64.

The optical side of a SONET/SDH signal is known as the Optical Carrier (OC) [5]. Higher-bit-rate signals are defined analogous to both SONET and SDH, as shown in Table II.1

Table II. 1: SONET/SDH Signal and Bit-Rate Hierarchy.

SONET Signal (Electrical)	Equivalent SDH Signal (Electrical)	Optical level	Bit Rates (Mbps)
STS-1	–	OC-1	51.84
STS-3	STM-1	OC-3	155.52
STS-12	STM-4	OC-12	622.08
STS-48	STM-16	OC-48	2488.32
STS-192	STM-64	OC-192	9953.28
STS-768	STM-256	OC-768	39813.12

II.2.2 Wavelength Division Multiplexing

Wavelength Division Multiplexing (WDM) is one of the most important fiber optic transmission technology used in telecommunication networks. It responds to the growing need for efficient and capable data transmission by working with different formats, such as SONET/SDH, while increasing bandwidth and maintaining system performance

The basic concept of a WDM is illustrated in Figure II.1. It involves the process of combining multiple wavelengths onto a single optical fiber. The optical signal reaching the receiver is then demultiplexed into separate channels by using a suitable optical device.

The space between channels is reduced by increasing the number of combined wavelength; however, the frequency spacing should be no less than the bandwidth of each channel to avoid inter-channel cross talk.

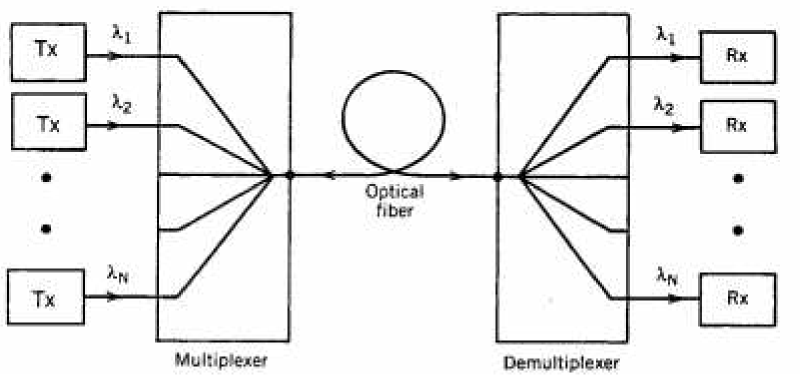


Figure II. 1: Wavelength Division Multiplexing Scheme [1].

II.2.2.1 Types of Wavelength Division Multiplexing

Depending on channel resolution, number of channels and the ability to amplify the multiplexed signals in the optical space, WDM systems are classified into two types; Coarse Wavelength Division Multiplexing (CWDM) and Dense Wavelength Division Multiplexing (DWDM). Table II.2 below illustrates the main difference between them.

CWDM uses increased channel spacing up to 16 channels (from 1480 nm - 1620nm windows) with 20 nm channel spacing. It is applied to short distance communication system with broad bandwidth [26].

Whereas, Dense WDM uses small interval between adjacent channels with working wavelength from 1550 nm to 1620nm. It can bear 8 ~ 160 wavelengths on one fiber with narrower wavelength spans. DWDM can transmit more data over a larger run of cable with less interference than CWDM system. Mostly, it is used in long-distance transmission system [26].

Table II. 2: Comparison between CWDM and DWDM.

	Channel Spacing	**Band used**	**Cost per channel**	**Number of Channels delivered**	**Best Application**
CWDM	Large,1.6nm -25nm	S,C and L	LOW	17 – 18 most	Short haul, Metro
DWDM	Small, 1.6nm or less	C and L	High	Hundreds of channels possible	Long Haul

II.2.2.2 Relationship between DWDM and SONET/SDH

The transmission capacity of the fiber network can be effectively improved through integrated application of DWDM and SONET/SDH. Both DWDM system and SONET/SDH system belong to the transmission network layer [26].

In terms of multiplexing, The SONET/SDH is the Time Division Multiplexing (TDM) system, it takes synchronous and asynchronous signals and multiplexes them to a single higher bit rate for transmission at a single wavelength over fiber. Source signals may have to be converted from electrical to optical or from optical to electrical and back to optical before being multiplexed. Whereas, the DWDM technology simultaneously transmits multiple optical carrier signals of different wavelengths in the same fiber, fully utilizing the bandwidth resources of fiber and increasing system transmission capacity [26].

Another fundamental difference between the two technologies is that WDM can carry multiple protocols without a common signal format, while SONET/SDH cannot. The relationship between DWDM system and some common services is shown in Figure II.2.

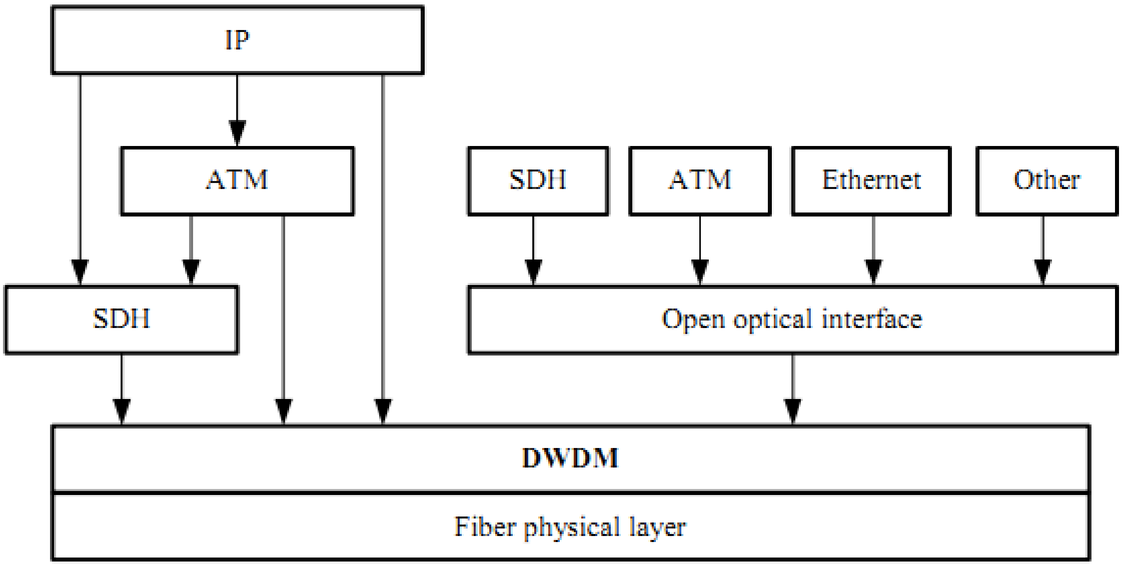


Figure II. 2: Relationship between DWDM and Other Services [26].

II.2.2.3 WDM Limitations

Crosstalk is one of the major limitation in DWDM systems. When signals from one channel arrive in another, they become noise in that channel. This can have serious effects on the Optical Signal-to-Noise Ratio (OSNR) and hence on the error rate of the system. Crosstalk is quoted as the loss in dB between the input level of the signal and its interferer signal strength in the adjacent channel. A figure of 30 dB is widely considered an acceptable level for most systems. Two kinds of crosstalk exist, depending on their source [10].

- **Inter-band Crosstalk:** which is situated in wavelengths outside the channel slot. It can be removed with narrow-band filters and it produces no beating during detection. In a DWDM networks, inter-band crosstalk appears from channels of different wavelengths.

- **Intra-band Crosstalk:** which is situated within the same wavelength slot. It occurs when the signal and the interferer has the closely valued wavelengths. Intra-band Crosstalk cannot be removed by an optical filter and therefore accumulates through the network.

II.2.3 Open Transport Network

Open Transport Network (OTN) is a fiber optic backbone developed by the International Telecommunication Union - Telecommunications Standardization Sector (ITU-T) initially using SONET/SDH as the underlying technology and DWDM flexibility to offer a wealth of interfaces, unmatched availability and a powerful management system at high capacity. Its simplicity in installation and maintenance is unprecedented [40].

This technology combination is called open because it offers the right interface to transport data in any format. Transport because each application has its garneted bandwidth irrespective to the distance that need to be bridged which means 100% quality of service; and Network because the network must be available in all circumstances to avoid any delay in responding to external events which may cost companies a fortune [40].

II.2.3.1 Open Transport Network Frame Structure

OTN system consists of three layers: the Optical Channel (Och), the Optical Multiplex Section (OMS) and the Optical Transmission Section (OTS) [5]. Each of the OTN layers is associated with a frame structure and appropriate overheads. Below, we examine the payload and overhead fields of the Och.

- **The Optical Channel Frame**

The OTN frame is very similar to a SONET frame in its structure and format; it is organized into 4 rows and 4080 columns of bytes [4]. A frame is transmitted serially starting with row 1, and per row from the left to right. Each row is composed of 16 interleaved and Forward Error Correction (FEC) blocks of 255 bytes, which is a total of 16 × 255 = 4080 bytes. Each block has 1 byte of overhead, 238 bytes of payload and 16 bytes of redundant FEC bytes, which refers to forward error correction that is used to detect and correct bit errors caused by physical impairments in the transmission links and enables transmission at higher rates without degrading the performance [5]. As shown in Figure II.3, there are three overhead areas in an OTN frame: the Optical Payload Unit (OPU) overhead, the Optical Data Unit (ODU) overhead and the Optical Transport Unit (OTU) overhead. These overhead bytes provide path and section performance monitoring, alarm indication, communication and protection switching capabilities. One additional feature is the inclusion of a FEC function for each frame. The FEC improves the OSNR by 4 to 6 dB, resulting in longer spans and fewer regeneration requirements.

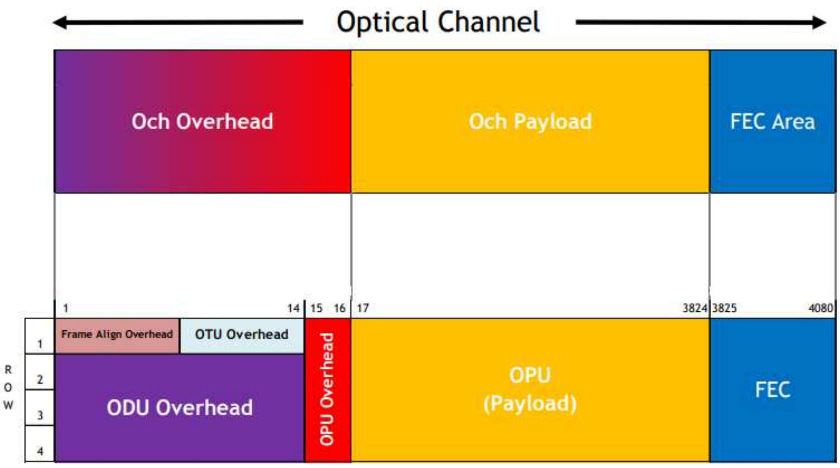


Figure II. 3: OTN Frame Structure [34].

II.3 DWDM Equipment

Typically, the components used in a DWDM system are: optical transmitters and receivers, transponders (wavelength converters), DWDM Multiplexer/Demultiplexer (Mux/DMUX), Optical Add/Drop Multiplexers (OADM), Optical Cross Connect (OXC), Optical Supervising Channel (OSC), optical amplifiers and dispersion compensation techniques.

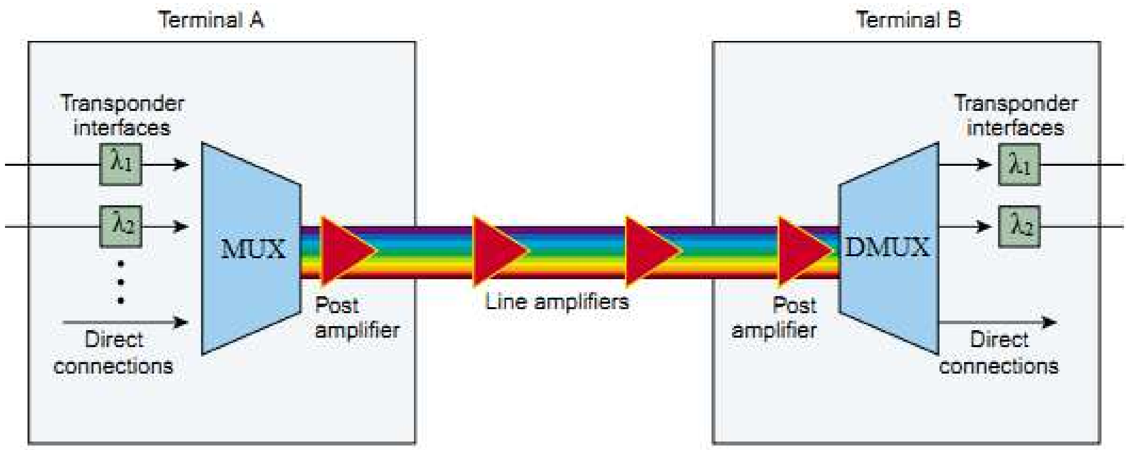


Figure II. 4: DWDM Components [9].

II.3.1 Transponder

The system shall support a combination of grey client interfaces - STM-16, STM-64, Gigabit Ethernet and 10G Ethernet LAN and WAN… etc. Various sets of transponders are added to translate these client interfaces. Each signal in the fiber has a corresponding wavelength-converting transponder, which is an Optical-Electrical-Optical (O-E-O) wavelength converter. It maps the grey input optical clients to a colored DWDM wavelength (using a 1550nm band laser) towards Mux/DMUX block and vice-versa by performing the 3R function, which consists of re-timing re-transmitting, and reshaping the received signal.

II.3.2 Multiplexer

Multiplexer (MUX) receives the converted signals from the transponder with different wavelength ranging from λ_1 to λ_n and combine them onto a single outgoing line to be transmitted simultaneously.

II.3.2.1 Optical Add and Dropp Multiplexer

The OADM performs the drop or insert of one or more wavelengths at some point along the transmission span. Rather than combining or separating all wavelengths, the OADM can drop some while passing other ones. It can be used at different points along the optical link to insert/remove or route selected channels increasing the network flexibility.

It is widely needed for WAN and Metro-Area Networks(MAN) in which one or more channels need to be dropped or added while preserving the integrity of other channels.

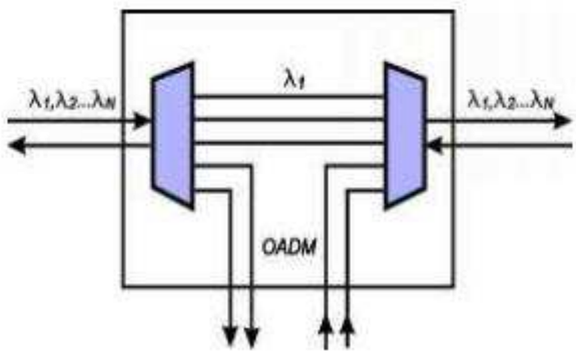


Figure II. 5: Optical Add and Drop Multiplexer [36].

II.3.2.2 Optical Cross-Connect

An Optical Cross-Connect (OXC) is an N × N optical switch with N input fibers and N output fibers. The OXC can switch optically all of the incoming wavelengths of the input fibers to the outgoing wavelengths of the output fibers. For instance, it can switch the optical signal on incoming wavelength λ_i of input fiber k to the outgoing wavelength λ_i of output fiber m [5]. A typical 8 x 8 OXC connection is represented in Figure II.6.

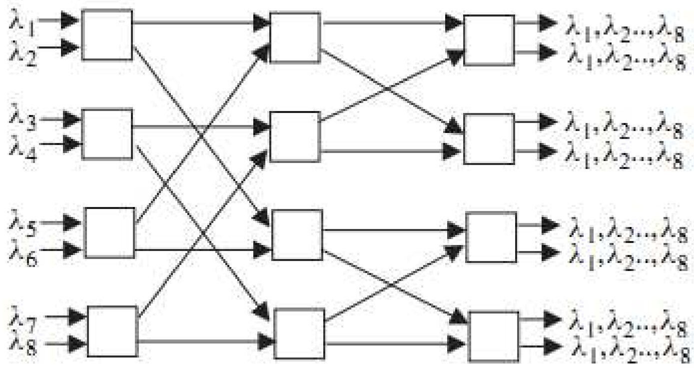


Figure II. 6: Banyan Network using 2x2 Couplers [5].

There are several different technologies for building a switch fabric of an OXC but large OXC switch fabrics can be constructed using 2 × 2 (3dB) couplers , arranged in a multi-stage interconnection network, such as a Banyan network. A 2 × 2 coupler is a 2 × 2 directional switch, which can direct the optical signal on any input i to any output j [5].

II.3.3 Demultiplexer

Optical Demultiplexer (DMUX) is a passive optical filter system, which are arranged to process specific wavelengths out of the transport system. It breaks the multi-wavelength signal back into individual signals and sends its outputs into the end transponder to be mapped to different client interfaces.

II.3.4 Optical Supervising Channel

The supervision information transmitted on the Optical Supervising Channel (OSC) is the information related to all kinds of optical amplifiers, such as input/output optical power of the amplifier and working wavelength of pump light source as well as remote conditions at the optical terminal. Therefore, when the optical amplifier is failed, the OSC cannot work normally. It is always terminated at intermediate amplifier sites where it receives local information before retransmission for maintenance purposes.

II.3.5 Optical Amplifiers

For the long-distance optical transmission, optical power gradually decreases due to attenuation. It is necessary to compensate these losses by boosting the signal at several levels of the link using optical amplifiers.

Optical amplifier is the technology for solving power limits without O-E-O conversion; it directly amplifies the optical signals. The amplification is achieved by several types of amplifiers but the most common ones are the EDFAs and Raman amplifiers.

II.3.5.1 Erbium Doped Fiber Amplifier

Erbium (Er^{+3}) is a rare-earth element that, when excited, emits light around 1.54 µ, which is the low loss wavelength for optical fibers used in DWDM. A weak signal enters the EDFA, into which light at 980 nm or 1480 nm is injected using a pump laser. This injected light stimulates the erbium atoms to release their stored energy as additional 1550-nm light. As a result, down the fiber the signal strength grows stronger [30].

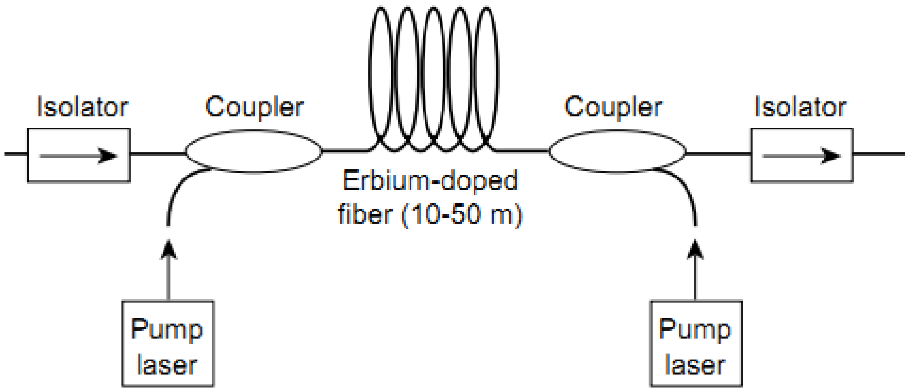


Figure II. 7: Erbium Doped Fiber Amplifier [9].

II.3.5.2 Raman Amplifier

The Raman fiber amplifier uses the gain mechanism generated by non-linear SRS in the fiber to amplify the optical signals. The SRS converts the energy of short-wavelength pump light into the energy of long-wavelength signal light, to amplify the signal light. It operates around 1330 nm and 1550 nm with pumps at 1240 nm and 1420 nm respectively. The pump photon has to lose its energy to create another photon at a lower frequency and lower energy. The difference in energy creates optical phonons, which are absorbed by the medium.

II.3.5.3 Semiconductor Optical Amplifier

The basic working principle of a Semiconductor Optical Amplifier (SOA) is the same as a semiconductor optical laser but without feedback. SOAs amplify incident light through simulated emission. When the light traveling through the active region, it causes these electrons to lose energy in the form of photons and get back to the ground state. Those stimulated photons have the same wavelength as the optical signal, thus amplifying the optical signal.

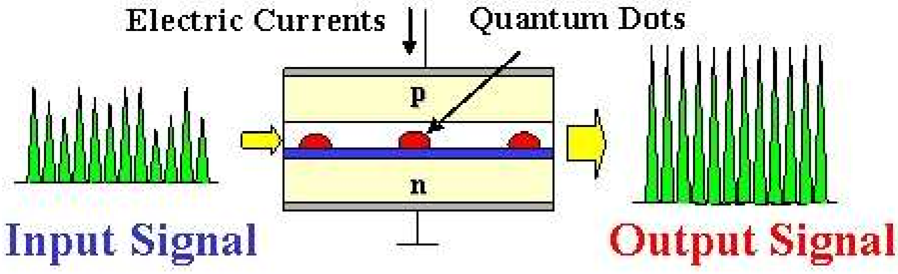


Figure II. 8: Semiconductor Optical Amplifier [33].

A comparison between the three optical amplifiers is summarized on the table II.3 below

Table II. 3: Comparison between EFDA SOA and Raman.

Properties	**Gain (dB)**	**Wavelength (nm)**	**Bandwidth (3dB)**	**Noise Figure (dB)**	**Pump power**
EDFA	>40	1530-1560	30-60	5	25dBm
Raman	>25	1280-1650	Pump dependent	5	>30dBm
SOA	>30	1280-1650	60	8	<400mA

II.3.6 Dispersion Compensation Techniques

The dispersion compensation is the most important feature required in optical fiber communication system to remove the spreading of the light pulses.

To compensate dispersion in WDM systems, various methods can be used, which are: Dispersion Compensating Fiber (DCF), Fiber Bragg Grating (FBG), Digital Filters, Optical Phase Conjugation and Electrical Dispersion Compensation. The most commonly used techniques are DCF and FBG. A comparative study between the two schemes is summarized in Table II.4.

II.3.6.1 Dispersion Compensation Fiber

DCF is a loop of fiber providing an optical medium with a relatively large negative chromatic dispersion factor (D (λ)) at the operating wavelength equal to the dispersion of the transmitting fiber. The positive dispersion of standard mode fiber in C and L band can be compensated by using DCF having high values of negative dispersion.

A DCF module should have low insertion loss, low polarization mode dispersion and low optical nonlinearity. By placing one DCF with negative dispersion after a SMF with positive dispersion, the net dispersion will be zero. The perfect condition for dispersion compensation is expressed by equation II.1

$$D_{SMF} \times L_{SMF} = -D_{DCF} \times L_{DCF} \quad \text{(II.1)}$$

Where D and L are the dispersion and length of each fiber segment respectively.

Depending on the arrangement of SMF and DCF in the link, there are three types of DCFs

- **Pre-Compensation**, in which DCF is placed before SMF .The designing consists of DCF, EDFA and SMF. The Purpose of EDFA is to provide periodic amplification.
- **Post-Compensation**, in which DCF is placed after SMF.
- **Symmetrical-Compensation**, in which DCF is positioned between two equal lengths of SMF.

II.3.6.2 Fiber Brag Gating

FBGs are made by laterally exposing the core of a SMF to a periodic pattern of intense ultraviolet light. The exposure produces a permanent increase in the refractive index of the fiber's core. At each periodic refraction change, a small amount of light is reflected. All the reflected light signals are combined coherently to one large reflection at a particular wavelength when the grating period is approximately half the input light's wavelength. This is referred to as the Bragg condition and the wavelength at which this reflection occurs is called the Bragg wavelength. Light signals at wavelengths other than the Bragg wavelength, which are not phase matched are essentially transparent and will be transmitted. This is shown in Figure.II.9.

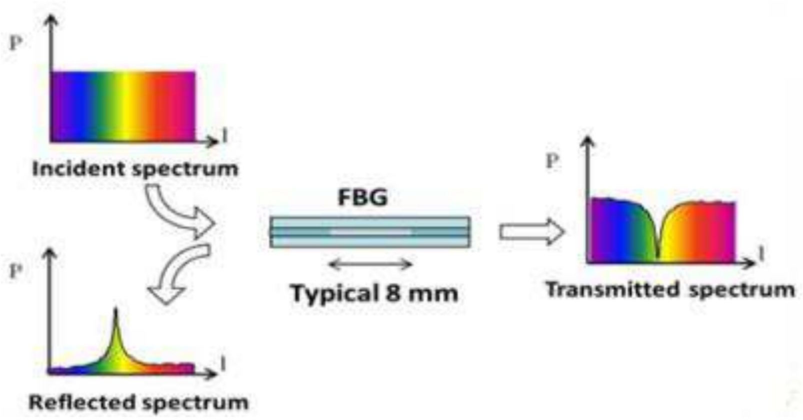


Figure II. 9: Spectral Response of FBG [39].

A comparison between the compensation techniques is tabulated below

Table II. 4: Comparison between DCF and FBG.

Characteristics	Attenuation	Insertion Loss	Nonlinear Effect	Bandwidth	Fiber Length	Overall Cost
DCF	0.8 dB/km	High	Some limitations	Wide band, 20nm	17-20 km	High
FBG	0.2 dB/km	Low	no	Narrow band, 01-5nm	10-15 cm	Low

II.4 Parameters Affecting System Design

Initially, fiber loss was considered as the biggest factor in limiting the length of an optical channel. However, as data rates grow and pulses occupy lesser and lesser time slots, group velocity dispersion and nonlinearities become considerable. As we will see in the following sections, an optical link is designed by taking into account some performance parameters, which are generally: Q factor and BER of the system.

II.4.1 Q Factor

Q-factor is a parameter used to measure the quality of the optical communication system and determine the BER. It measures the quality of an analog transmission signal in terms of its OSNR by taking into account physical impairments of the signal that cause its degradation and bit errors like noise, chromatic dispersion and non-linear effects. The higher the value of Q, the better the quality of the system.

System performance is estimated in terms of BER. Bit Error Rate is not counted directly but measured by the evaluation of statistical fluctuations, which are characterized by Q-factor. The Q-factor is defined as:

$$Q = \frac{|\mu_1 - \mu_0|}{\sigma_1 + \sigma_0} \tag{II.2}$$

Where: μ_1, μ_0 are the average value of received signal at sampling instants when a logical 1 or 0 is transmitted and σ_1, σ_0 are the standard deviations respectively.

II.4.2 Bit Error Rate

Bit Error Rate (BER) is defined as the percentage of bits that consists errors with respect to the total number of bits received during a transmission. It is an indication of how often a packet or other data unit has to be retransmitted. In case of WDM networks, the requirement of a BER is about (10^{-9} to 10^{-12}), which means that the corruption of bits during transmission can happen at one out of every 10^{12}.

Knowing the Q-factor, the BER can be estimated by equation II.3

$$BER = \frac{1}{2}\, \text{erfc}\,(\frac{Q}{\sqrt{2}}) \qquad (II.1)$$

Figure II.10 shows the relation between BER versus Q Factor. As we can see, when the bit error rate increases the quality of signal decreases.

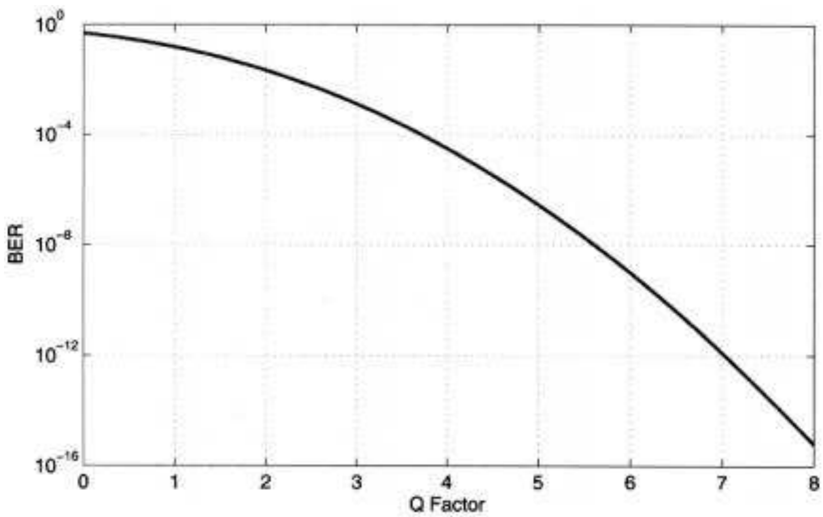


Figure II. 10: Bit-Error Rate versus the Q parameter [1].

II.5 Conclusion

The emergence of DWDM is one of the most important phenomena in the development of fiber optic transmission technology. Although this technology is complex and sensitive to amplitude variations and reflections, it is widely adopted for its advantages that include huge bandwidth, low signal distortion and low power requirement.

DWDM is applied to all networking topologies in telecommunication infrastructure community. The next chapter will be devoted to show these different topologies and we will focus on the application of star topology related to FTTH, which consist of delivery of a communications signal over optical fiber from the operator’s switching equipment all the way to the home.

Chapter III

Application of Star Topology in FTTH Technology

III.1 Introduction

This chapter is devoted to star topology and its application in FTTH technology that we have seen in our training in *Algerie Telecom*. Firstly, an overview about the used topologies in DWDM is provided, especially star topology. Furthermore, the technology of FTTH and its different architectures is studied. Finally, the main components of Passive Optical Network (PON) networks is discussed.

III.2 DWDM Network Topologies

The network structure formed due to the interconnectivity patterns is known as a topology, which can take a form of a point-to-point, star, ring or a mesh structure. Each of these methodologies has its own particular advantages and limitations in terms of reliability, expandability and performance characteristics. For more details about the different topologies, see appendix -B-. The Figure III.1 depicts these four configurations.

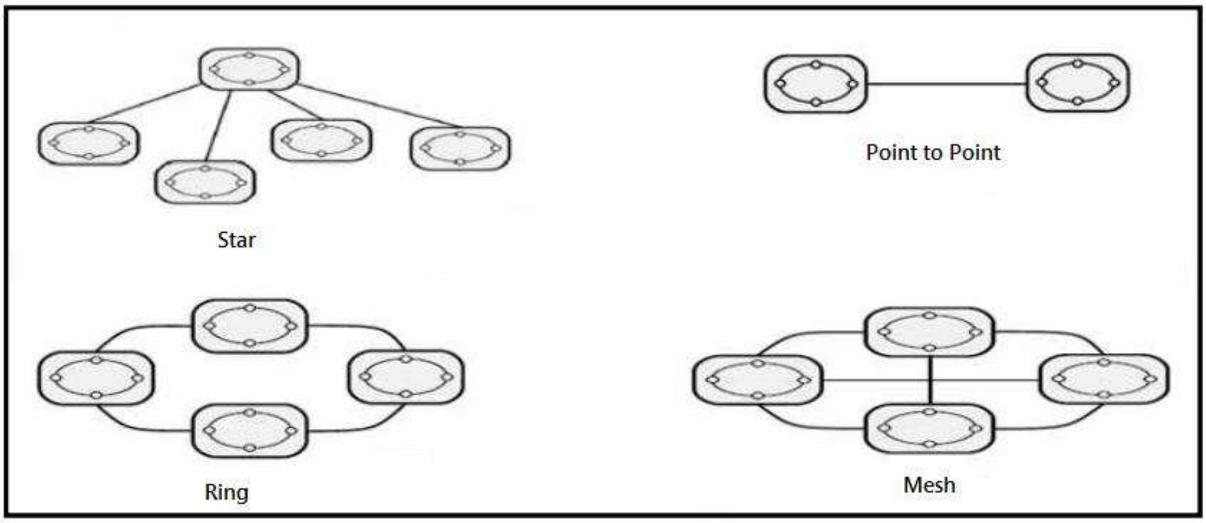


Figure III. 1: Different DWDM Topologies.

III.3 Star Network Topology

A star topology is one of the most used LAN topology because of the low cost and the ease of troubleshooting. In this topology, each end station is connected to a central node using a point-to-point connection. Access from any end station on the network to any other end station is accomplished through the central node. This central node broadcasts all transmissions received from any peripheral node to all peripheral nodes on the network, sometimes including the originating node. All peripheral nodes may thus communicate with all others by transmitting to, and receiving from, the central node only. The star may be active or passive. In an active star, the incoming signal is converted into the electrical domain and then distributed to each node. In passive star, the distribution occurs in the optical domain via passive star N x N coupler. Figure III.2 illustrates a star network topology.

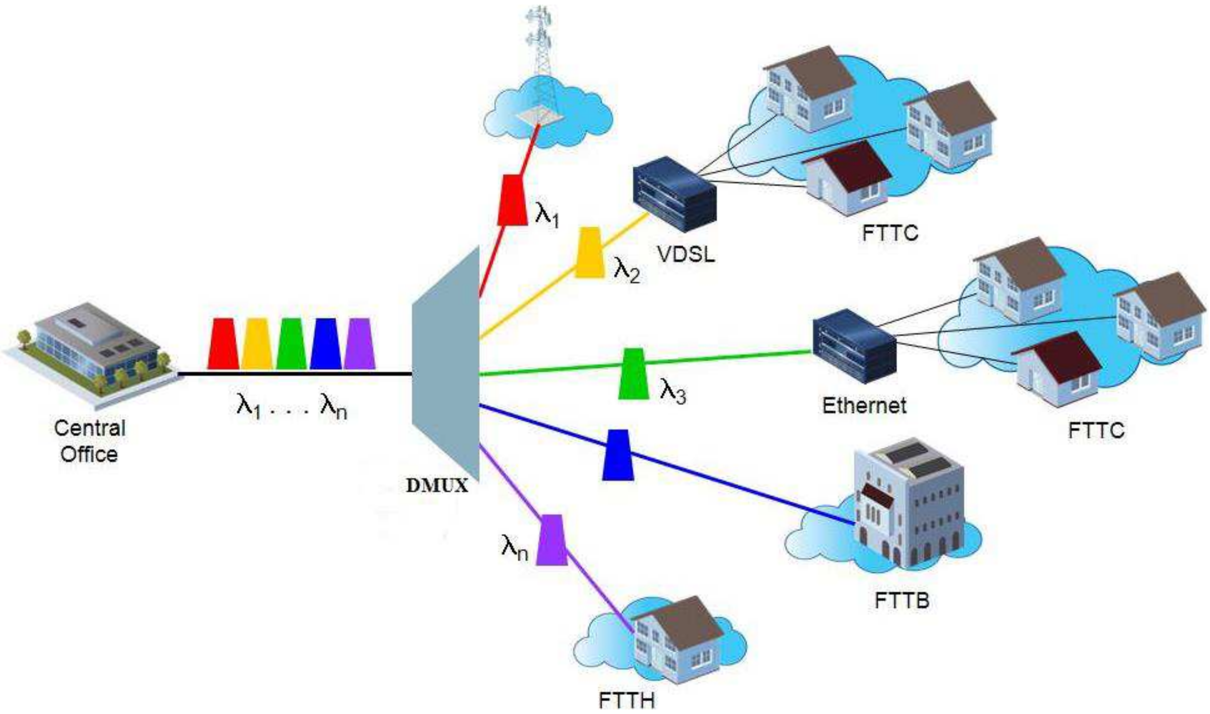


Figure III. 2: Star Topology [35].

III.4 Application of Star Topology in Fiber to the Home Technology

Star topology networks have been used effectively in Fiber to the home technology.

III.4.1 Definition of Fiber to the Home

Fiber to the Home, commonly known as FTTH, is a network connection using optical fiber directly from the access network to the home. The optical fiber communication's path is terminated on inside the subscriber's homes for carrying communication services with greater bandwidth and highest possible speed of internet to a single subscriber.

III.4.2 Fiber to the Home Networks Architecture

There are two important types of systems that make FTTH broadband connections possible: Active Optical Networks (AON) and Passive Optical Networks (PON).The choice of active or passive architectures for deployment depends on the type of services to be delivered, coat of the infrastructure, current infrastructure and future plants for migrating to the new technologies.

III.4.2.1 Active Optical Networks

Active optical network (AON), also called point-to-point network, usually uses active devices and electrically powered switching equipment, such as router or switch aggregator to manage signal distribution and direct signals to specific customers. This switch opens and closes in various ways to direct incoming and outgoing signals to the proper place [43].

III.4.2.2 Passive Optical Networks

Passive Optical Networks (PON) uses fiber and passive components like optical splitters to separate and collect optical signals as they move through the network [43].A PON shares fiber optic strands for portions of the network. Powered equipment is required only at the source and receiving ends of the signal. Further, the passive star can be a single wavelength system (all homes served by a common wavelength) or a WDM system (where each home is served by a different wavelength).

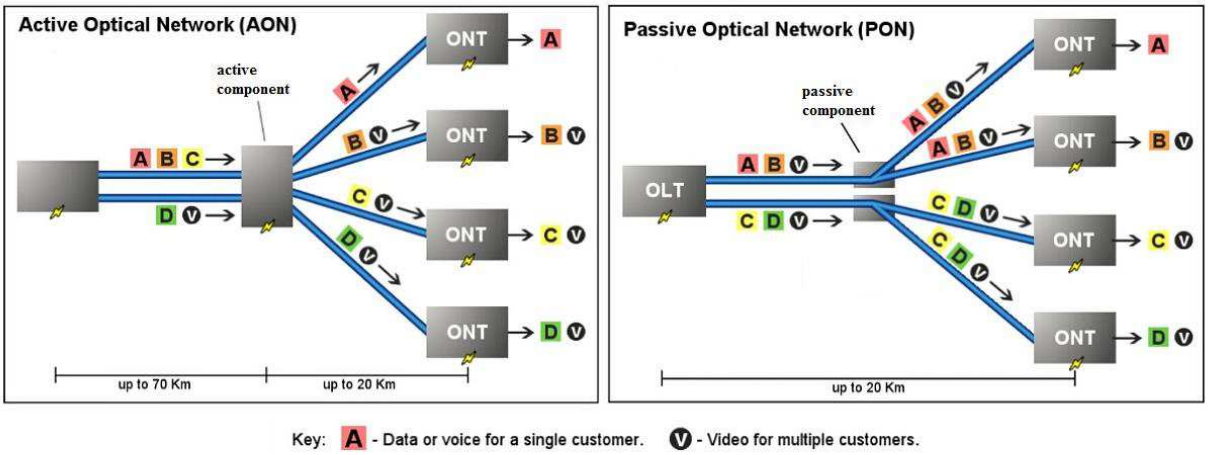


Figure III. 3: Typical AON and PON Architectures [43].

III.5 Passive Optical Networks architecture

In general PON network consists of the following device: an Optical Line Terminal (OLT) at the service provider’s central office, Fiber Distribution Frames (FDT), Fiber Access Terminal (FAT) usually placed at the entrance of the neighborhood and finally a number of Optical Network Terminals (ONTs) close to end users and The splitter also denoted as passive since it is passive power divider (Figure III.4).

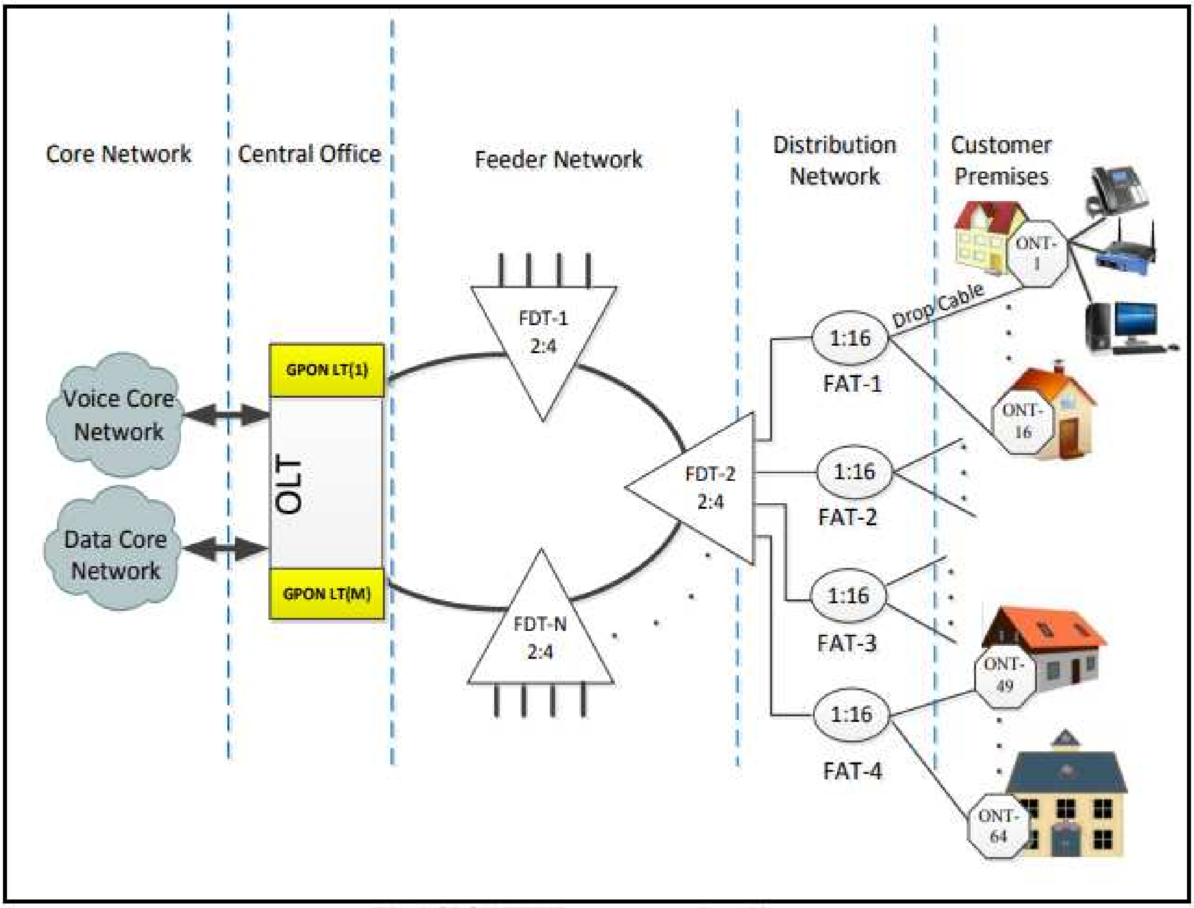


Figure III. 4: Passive Optical Network Architecture [25].

III.5.1 Optical Line Terminal

The Optical Line Terminal (OLT) is the main element of the network and it is the engine that drives FTTH system [29].The most important functions that OLT performs are traffic scheduling, buffer control and bandwidth allocation [27].OLTs typically operate using redundant DC power (-48VDC) and have at least 1 Line card for incoming internet, 1 System Card for onboard configuration and 1 to many Gigabit Passive Optical Networks (GPON) cards. Each GPON card consists of a number of GPON ports [25].For more details about GPON protocol, see appendix-C- .

OLT boards can handle up to 768 point-to-point connections in case of active ethernet for applications or clients that require this dedicated channel. However, it can provide up to 16,384 subscribers based on 64 users per GPON connection.

III.5.2 Fiber Distribution Frames

The feeder area extends from Optical Distribution Frames (ODF) in the Central Office (CO) to the distribution points. These points are called Fiber Distribution Frames (FDT) where level-1 splitters usually reside. The feeder cable is connected as ring topology starting from a GPON port and terminated into another GPON port as shown in Figure III.4 to provide line protection [25].Level-1 splitters with a spilt ratio of 2:4.This type of splitters enables the feeder to be connected to two GPON ports from one side and feeds four distribution cables from the other side. The fiber cable running between the CO and level-1 splitter is called Level-1 fiber [28].

III.5.3 Fiber Access Terminal

Fiber Access Terminal (FAT) is a pole-mounted box placed at the entrance of the neighborhood, it contains Level-2 splitter [25]. Usually, level-2 splitter is 1:16, which means each FAT serves 16 homes. The fiber cable running between level-1 splitter and level-2 splitter is called level-2 fiber.

III.5.4 Optical Network Terminals

Subscriber premises are connected to level-2 splitter inside the FAT by drop cables (level-3 fibers) [25].These cables have less fiber count and length ranges up to 100 meters, they are designed with attributes such as flexibility, less weight, smaller diameter, ease of fiber access and termination. Level-3 fibers are terminated at the entrance of the subscriber home with an Access Terminal Box (ATB) then an indoor drop cable connects the ATB to the ONT. Finally a patch cord connects the ONT to user’s devices.

III.6 Conclusion

In this chapter, passive star optical network technology is introduced in detail, especially FTTH system including all the major steps that a signal passes through all away to the subscriber. The next chapter will be devoted for simulating another application of star topology, which uses OXC system that is implemented inside the DWDM module.

Chapter IV

Simulation of DWDM Star Network

IV.1 Introduction

In this chapter, an eight channel DWDM star network is designd and analyzed using OptiSystem v.7.0 Simulator. This suggested system is demonstrated using an SMF, the dispersion of which is compensated with an equivalent length of DCF with EDFA. The choice of EDFA and DCF is made according to tables II.3 and II.4 respectively

The purpose of this simulation is to study the effect of the bit rate, the input power and dispersion compensation techniques on the DWDM system performance. Hence, this system will be simulated first without dispersion compensation then by applying DCF pre- and post-compensations at various operating bit rates ranging from 2.5 Gbps to 80 Gbps with different input powers in the range of -10 dBm up to 10 dBm. Further, the results are examined in terms of BER.

IV.2 DWDM Star Architecture Design

In this section, the block diagram used to build DWDM star architecture with its specific components and the designed system using OptiSystem software are presented.

IV.2.1 Design Consideration

The block diagram of the proposed design is depicted in Figure IV.1 below. It describes the basic optical communication system, which consists of a transmitter, a transmission link, an OXC and a receiver.

IV.2.1.1 Transmitter Design of 8-Channel DWDM System

Externally modulated transmitter is used in this design in order to achieve stability. This also has the benefit of reducing chirps, non-linear effects and the spacing among the neighboring channels. PRB sequence generator, NRZ pulse generator and Mach-Zehnder modulator are used and equally spaced laser array is deployed to feed laser signals having frequency spacing of 100 GHz starting from 191.1 THz.

IV.2.1.2 Transmission Link Design

The optical fiber used is SMF because it can yield to a high data rate, less dispersion and operate in long haul distance.

IV.2.1.3 Optical Cross Connect

The considered OXC is built using an eight 2 x 2 optical couplers that act as splitters to distribute the power among the users.

IV.2.1.4 Receiver Design

Optical receiver is used with cutoff frequency set to 0.75*Bit rate. The DMUX receives the composite signal and diverts it to 8 various detectors. Each signal is analyzed using BER analyzer.

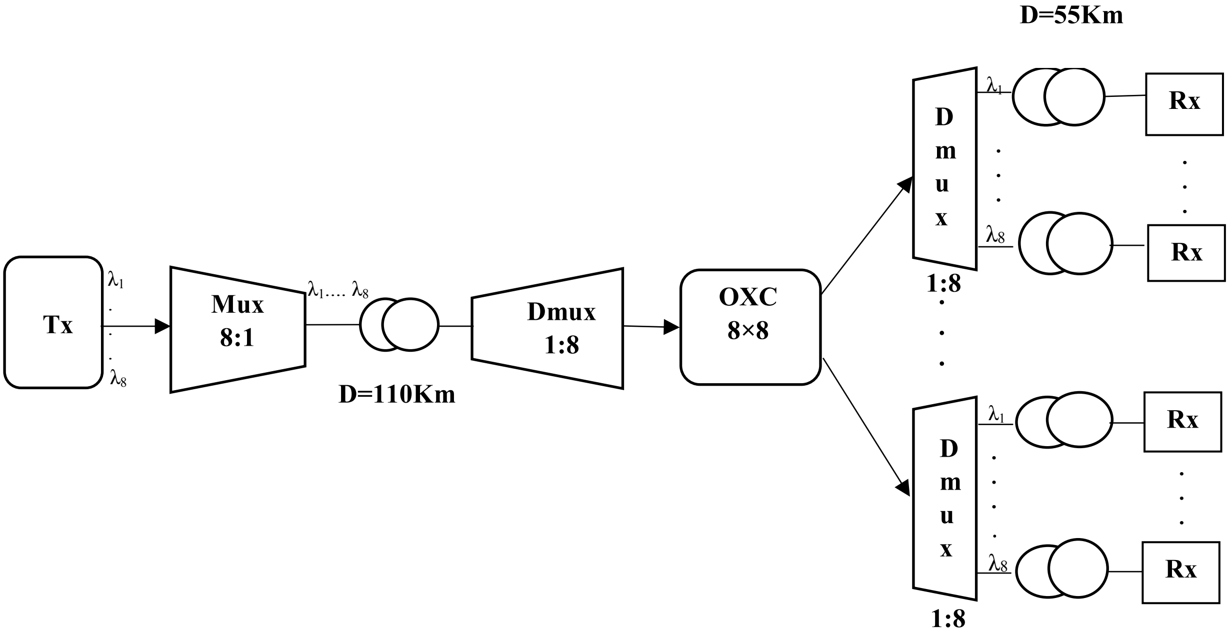


Figure IV. 1: Block Diagram of DWDM Star Network.

In this system, EDFA and DCF were used after each fiber to compensate the span loss and chromatic dispersion. The length of DCF is calculated according to equation (II.1). The design of both types of dispersion compensation used are presented the following figures.

- **Pre-Compensation**

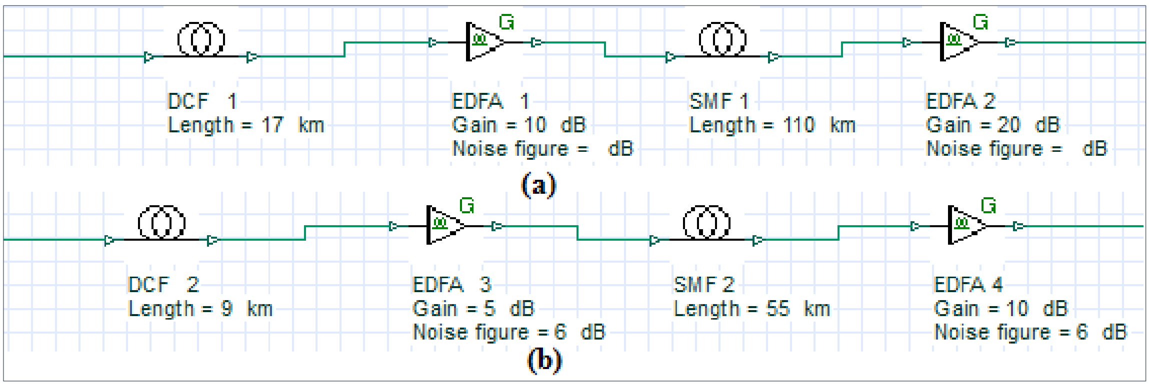


Figure IV. 2: Optical Link Structures Within Pre-Compensation Technique for (a) SMF_1 (b) SMF_2.

- **Post-Compensation**

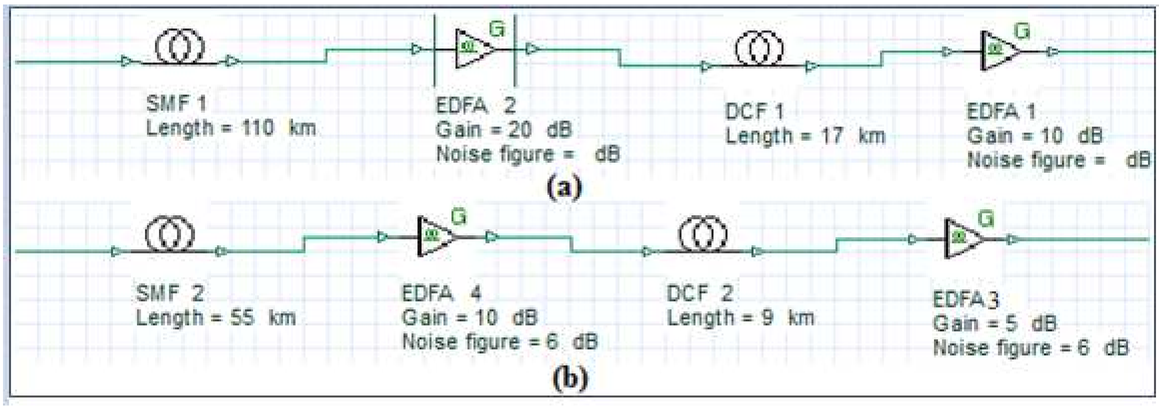


Figure IV. 3: Optical Link Structures Within Post-Compensation Technique for (c) SMF_1 (d) SMF_2.

The parameters of SMF, DCF and EDFA for communication channel design are shown in Tables IV.1 and IV.2 respectively.

Table IV. 1: Parameters of SMF and DCF.

Parameters	SMF_1	DCF_1	SMF_2	DCF_2
Length (Km)	110	17	55	9
Attenuation (dB/Km)	0.2	0.5	0.2	0.5
Dispersion (ps/nm/Km)	17	-110	17	-110
Differential slope(ps/nm^2 /Km)	0.075	-0.3	0.075	-0.3
PMD coefficient (ps/Km)	0.5	0.5	0.5	0.5

Table IV. 2: EDFA Parameters.

Parameters	$EDFA_1$	$EDFA_2$	$EDFA_3$	$EDFA_4$
Gain (dB)	10	20	5	10
Noise Figure (dB)	Software Value	SoftwareValue	6	6

IV.2.2 Optisystem Designed Network

OptiSystem is a powerful software design tool that enables simulation of optical link with advanced and highly parameterized optical fiber models. Based on this simulator, an eight channel DWDM star optical network is simulated and analyzed.

IV.2.2.1 The Overall System

DWDM star network simulation setup is illustrated in Figure.IV.2

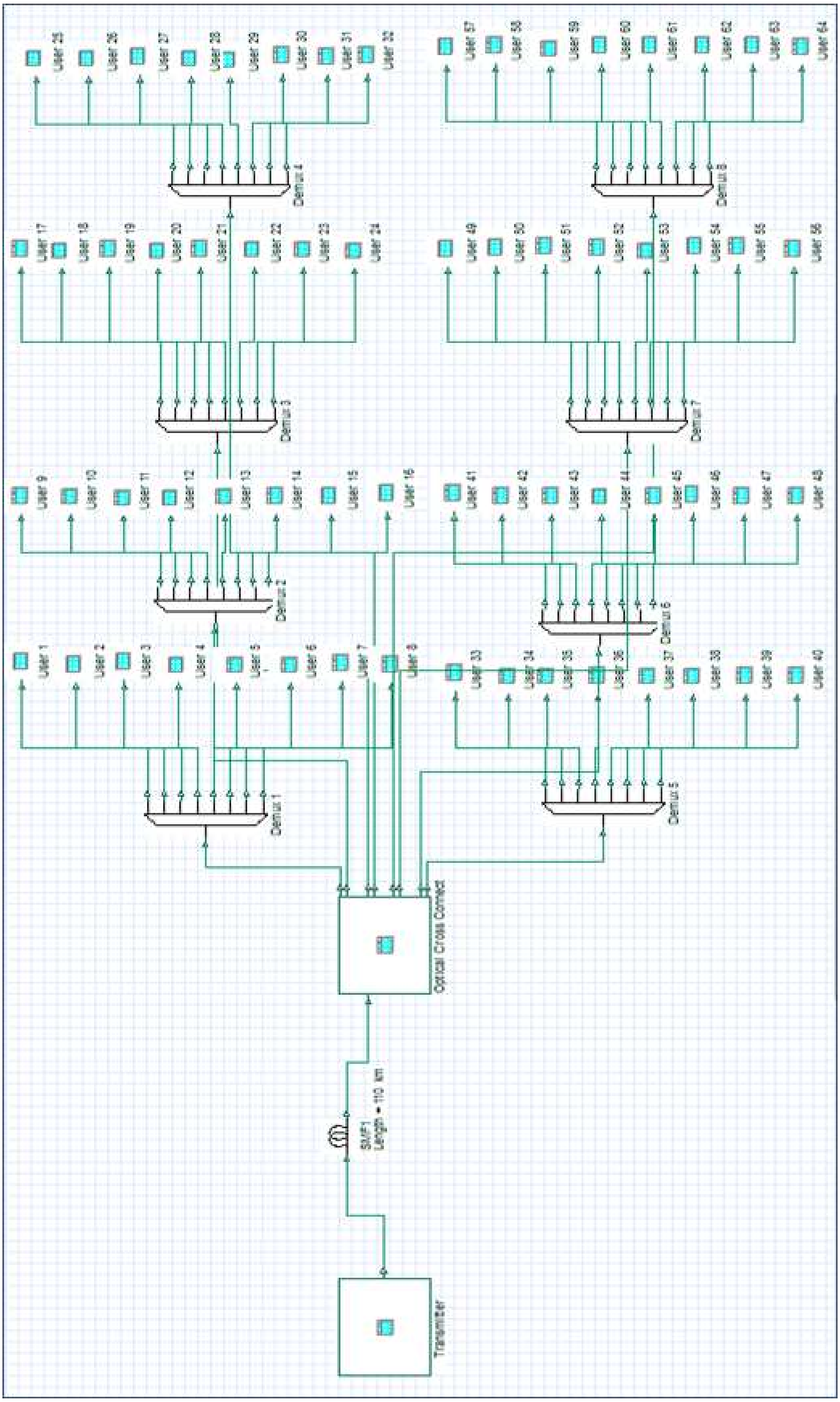


Figure IV. 4: Simulation Setup of DWDM Star Network.

IV.2.2.1 Subsystems Description

Transmitter, OXC and users description is shown in Figure IV.3

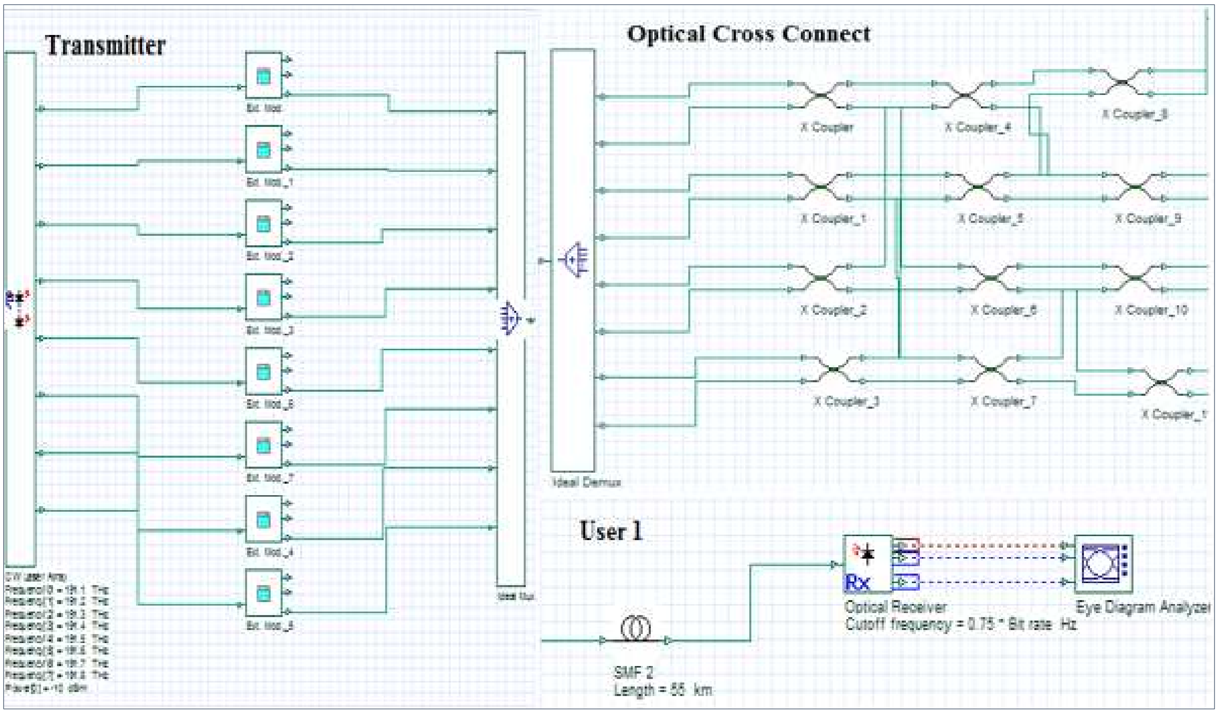


Figure IV.5: Subsystems Description.

The simulation is done based on the basic setup parameters, shown in Table IV.3.

Table IV. 3: Simulation Parameters.

Parameters	Value
Bit rate	2.5 Gbps to 80 Gbps
Input power	-10 dBm to 10 dBm
Transmission window	1550 nm
Number of channels	8

IV.3 Simulation Results

The design is evaluated by comparing the performance between conventional case (without compensation) and compensation method (pre and post-compensations) at various input power levels ranging from -10 dBm to 10 dBm for channel 1 having frequency of 191.1 THz.

Q factor and BER simulation results for 2.5, 10, 20, 30, 40 and 80 Gbps are summarized in the following tables.

Table IV. 4: Simulation Results for the System at 2.5 Gbps.

Input Power (dBm)	Without Compensation		Pre-Compensation		Post-Compensation	
	Q	BER	Q	BER	Q	BER
-10	0	1	23.89	$1.52e^{-126}$	23.45	$5.26\ e^{-122}$
-7.5	0	1	29.13	$4.68e^{-187}$	29.39	$2.44e^{-190}$
-5	0	1	33.05	$4.90e^{-240}$	34.11	$1.89e^{-255}$
-2.5	0	1	46.00	0	30.85	$1.86e^{-209}$
0	0	1	56.56	0	35.32	$9.74e^{-274}$
2.5	0	1	34.67	$5.97e^{-264}$	39.74	0
5	0	1	28.26	$2.92e^{-176}$	40.95	0
7.5	2.25	$1.21e^{-002}$	29.94	$1.67e^{-197}$	45.76	0
10	3.91	$4.61e^{-005}$	20.43	$2.97e^{-093}$	33.29	$1.74e^{-243}$

Table IV. 5: Simulation Results for the System at 10 Gbps.

Input Power (dBm)	Without Compensation		Pre-Compensation		Post-Compensation	
	Q	BER	Q	BER	Q	BER
-10	0	1	12.24	$7.08e^{-035}$	12.48	$3.63e^{-036}$
-7.5	0	1	16.42	$4.87e^{-061}$	16.65	$1.09e^{-062}$
-5	0	1	20.60	$9.10e^{-095}$	21.76	$1.69e^{-105}$
-2.5	0	1	23.19	$1.62e^{-119}$	27.15	$9.39e^{-163}$
0	0	1	24.04	$3.34e^{-128}$	34.90	$2.18e^{-267}$
2.5	0	1	22.41	$8.71e^{-112}$	46.01	0
5	0	1	16.65	$8.09e^{-063}$	46.46	0
7.5	0	1	11.30	$3.63e^{-030}$	28.85	$2.18e^{-183}$
10	0	1	6.33	$6.49e^{-011}$	12.63	$5.66e^{-037}$

Table IV. 6: Simulation Results for the System at 20 Gbps.

Input Power (dBm)	Without Compensation		Pre-Compensation		Post-Compensation	
	Q	BER	Q	BER	Q	BER
-10	0	1	9.10	$3.69e^{-020}$	8.79	$5.70e^{-019}$
-7.5	0	1	12.75	$1.11e^{-037}$	12.35	$1.89e^{-035}$
-5	0	1	16.75	$1.94e^{-063}$	16.58	$3.21e^{-062}$
-2.5	0	1	21.44	$1.79e^{-102}$	20.87	$3.07e^{-097}$
0	0	1	22.13	$5.24e^{-109}$	26.84	$3.75e^{-159}$
2.5	0	1	19.42	$1.61e^{-084}$	26.94	$1.75e^{-160}$
5	0	1	11.90	$3.16e^{-033}$	25.61	$4.27e^{-145}$
7.5	0	1	6.09	$3.25e^{-010}$	19.89	$1.76e^{-088}$
10	0	1	2.74	$1.84e^{-004}$	12.37	$1.85e^{-035}$

Table IV. 7: Simulation Results for the System at 30 Gbps.

Input Power (dBm)	Without Compensation		Pre-Compensation		Post-Compensation	
	Q	BER	Q	BER	Q	BER
-10	0	1	7.02	$8.71e^{-013}$	7.09	$5.35e^{-013}$
-7.5	0	1	9.76	$6.13e^{-023}$	9.97	$7.51e^{-024}$
-5	0	1	13.24	$1.72e^{-040}$	13.24	$1.83e^{-040}$
-2.5	0	1	16.70	$4.59e^{-063}$	16.41	$5.84e^{-061}$
0	0	1	19.61	$3.91e^{-086}$	19.33	$1.02e^{-083}$
2.5	0	1	17.49	$5.34e^{-069}$	18.58	$1.72e^{-077}$
5	2.21	0.01	11.25	$6.19e^{-030}$	16.27	$5.46e^{-060}$
7.5	3.08	$1.03e^{-003}$	6.11	$2.94e^{-010}$	12.17	$1.44e^{-034}$
10	4.05	$2.53e^{-005}$	3.26	$4.53e^{-004}$	7.71	$5.03e^{-015}$

Table IV. 8: Simulation Results for the System at 40 Gbps.

Input Power (dBm)	Without Compensation		Pre-Compensation		Post-Compensation	
	Q	BER	Q	BER	Q	BER
-10	0	1	5.97	$9.57e^{-010}$	5.25	$5.97e^{-008}$
-7.5	0	1	8.51	$5.51e^{-018}$	7.38	$5.85e^{-015}$
-5	0	1	11.31	4.18e-^{030}	9.85	$2.61e^{-023}$
-2.5	0	1	13.88	$2.98e^{-044}$	12.21	$1.02e^{-034}$
0	0	1	15.59	$2.97e^{-055}$	13.96	$1.02e^{-044}$
2.5	0	1	13.70	$3.42e^{-043}$	14.21	$2.85e^{-046}$
5	0	1	9.84	$2.22e^{-023}$	12.14	$2.22e^{-034}$
7.5	0	1	5.71	$3.11e^{-009}$	8.92	$1.48e^{-019}$
10	0	1	0	1	5.89	$1.29e^{-009}$

Table IV. 9: Simulation Results for the System at 80 Gbps.

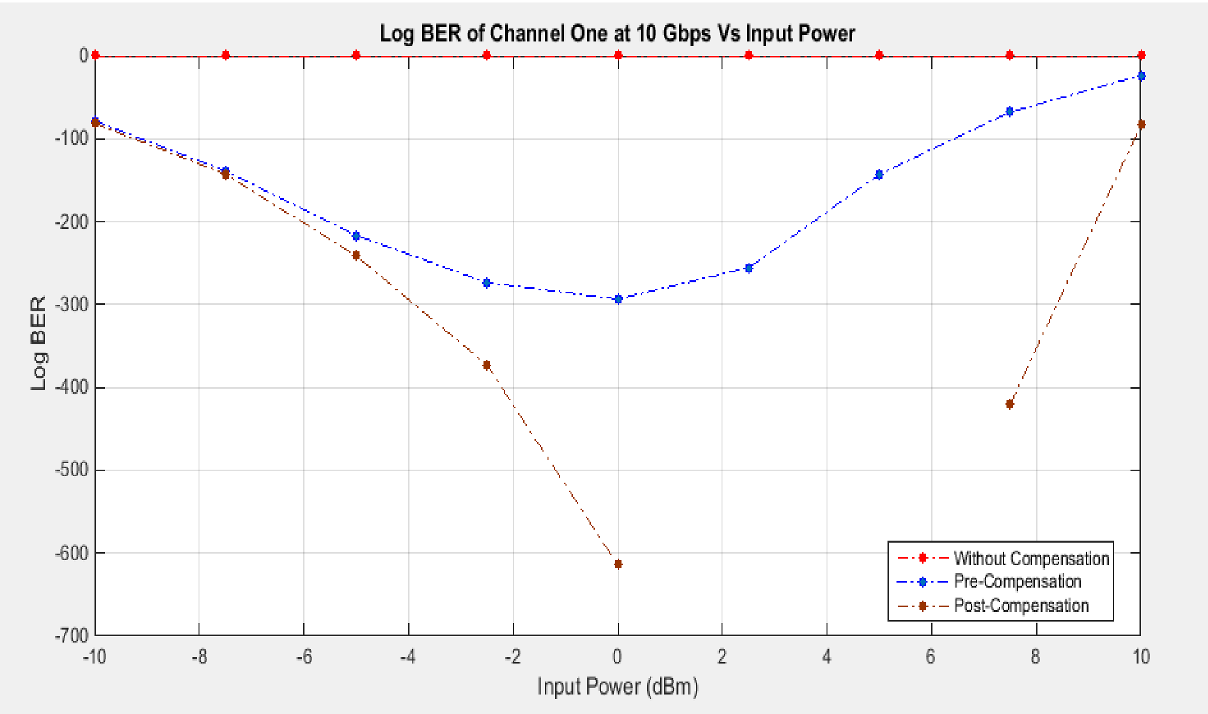
Input Power (dBm)	Without Compensation		Pre-Compensation		Post-Compensation	
	Q	BER	Q	BER	Q	BER
-10	0	1	0	1	0	1
-7.5	0	1	0	1	0	1
-5	0	1	0	1	0	1
-2.5	0	1	0	1	0	1
0	0	1	2.28	$8.13e^{-003}$	0	1
2.5	0	1	2.32	$7.31e^{-003}$	0	1
5	0	1	2.51	$4.87e^{-003}$	2.01	$1.55e^{-002}$
7.5	0	1	3.011	$1.29e^{-003}$	2.94	$1.62e^{-003}$
10	0	1	2.99	$1.34e^{-003}$	2.28	$8.95e^{-003}$

IV.4 Discussion

In order to facilitate the analysis of the system performance, BER versus input power are plotted for channel 1 using different compensation techniques and various bit rates. For a good transmission scheme BER should be below 10^{-009}.

IV.4.1 Result Discussion for Comparison between the Compensation Techniques

To compare between the compensation techniques, BER versus input power is plotted for channel 1 at 10 and 40 Gbps. The resultant graphs are represented in Figures below



FigureIV.6: BER vs Input Power Plot for Channel 1 at 10 Gbps.

- **At 10 Gbps**

  For conventional case, it is observed that the system performance is bad, whereas using compensation techniques the performence is better. From -10 to -5 dBm the two compensation techniques are good but beyond -5dBm post-compensation is preferable. The maximum Q factor is 46.46 and min BER is 0 obtained at P_{in} = 5 dBm for post-compensation.

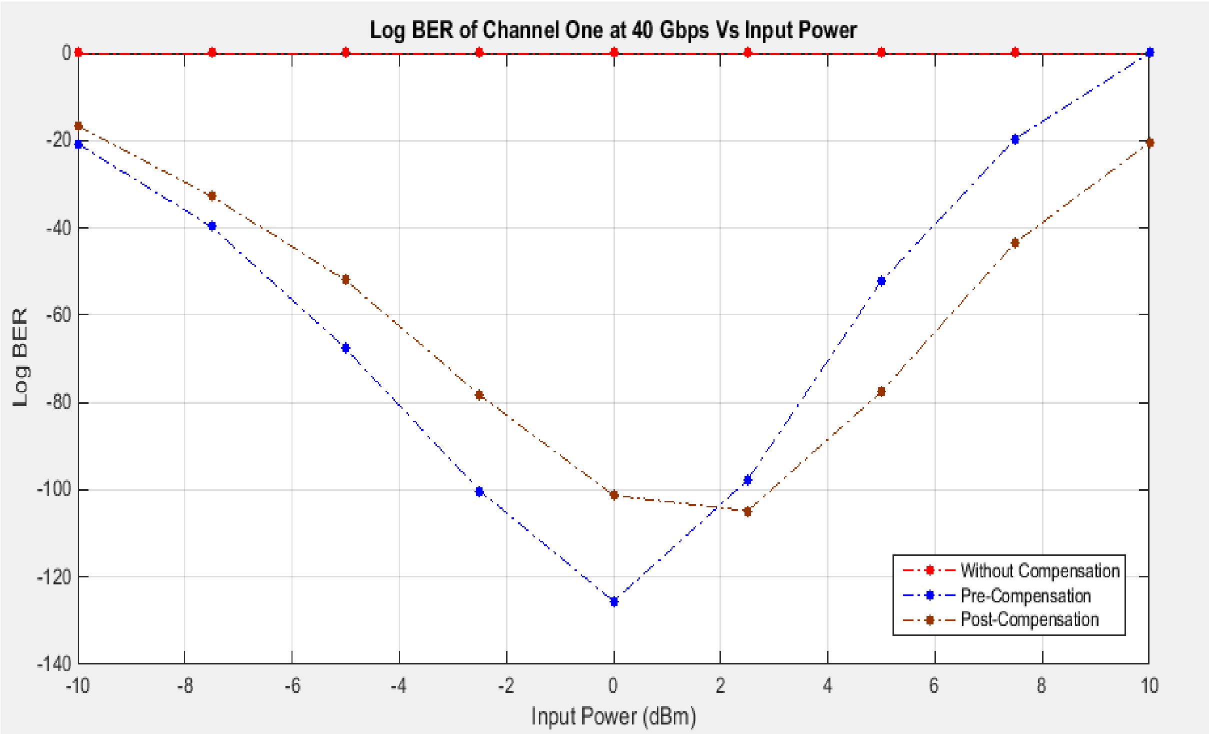


Figure IV. 7: BER vs Input Power Plot for Channel 1 at 40 Gbps.

- **At 40 Gbps**

For conventional case, it is noticed that the system performance is bad while using compensation techniques the performence is improved. From -10 to 0 dbm pre-compensation is preferable; however, beyond 0 dBm post-compensation provides better results. The maximum Q factor is 15.59 and min BER is $2.97e^{-055}$ obtained at P_{in} = 0 dBm for pre-compensation. This is well illustrated by the eye diagrams presented in Tables IV. 10 and IV.11 respectively.

Table IV. 10: Eye Diagram Results at 10 Gbps with Different Compensation Techniques.

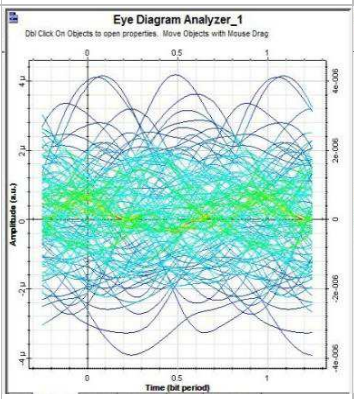
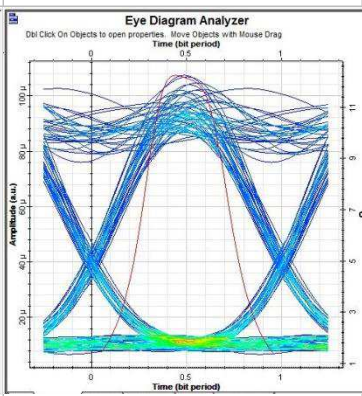
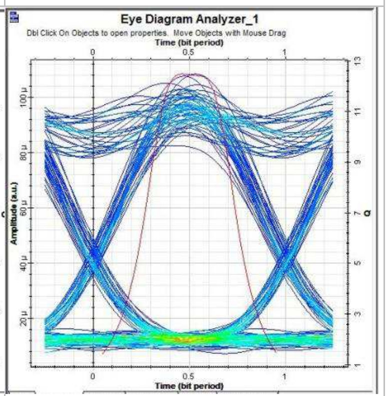
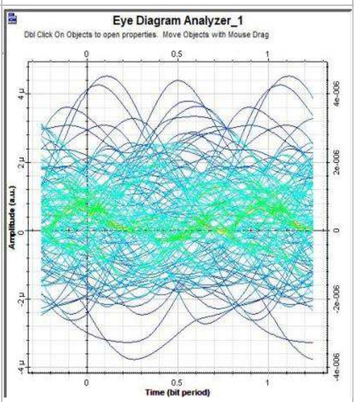
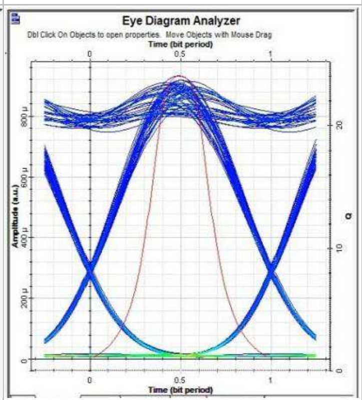
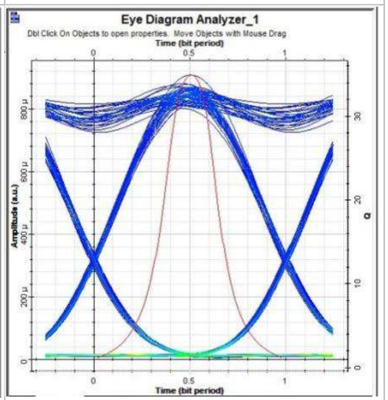
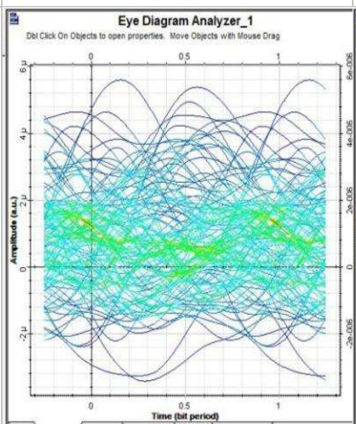
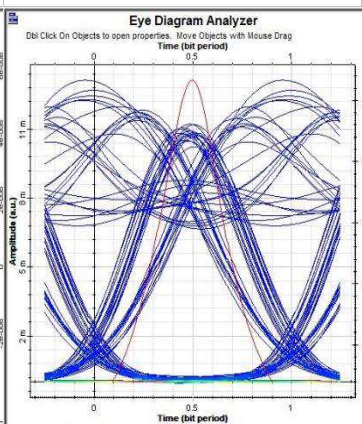
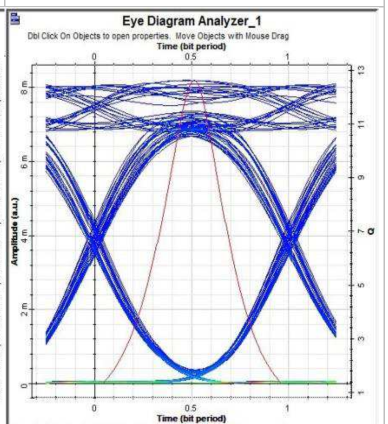
	10 Gbps		
	Without Compensation	**Pre-Compensation**	**Post –Compensation**
-10 dBm			
0 dBm			
10 dBm			

Table IV. 11: Eye Diagram Results at 40 Gbps with Different Compensation Techniques.

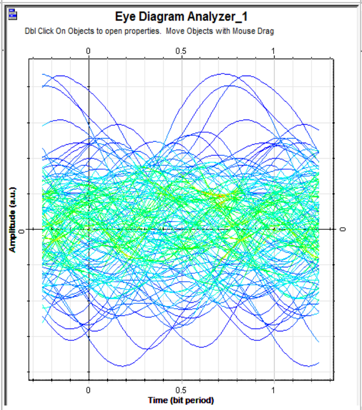
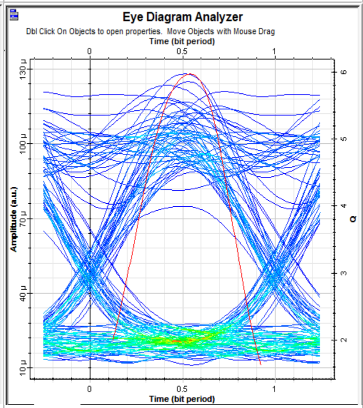
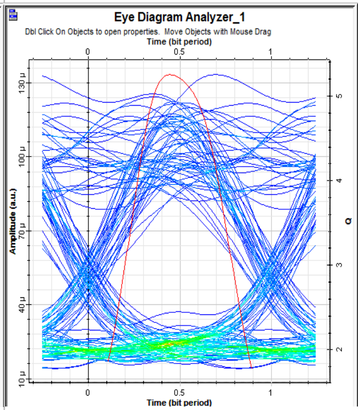
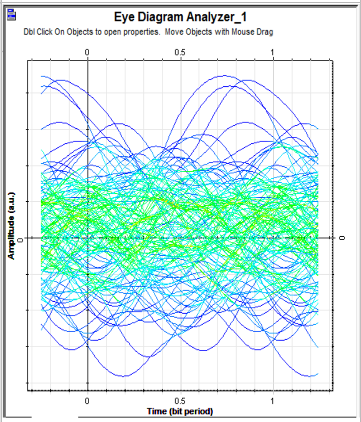
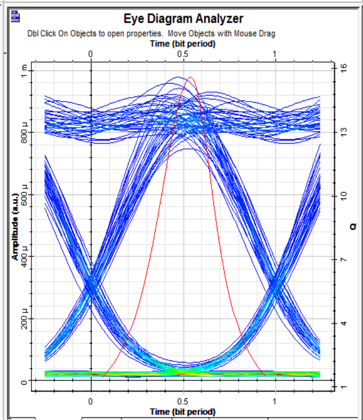
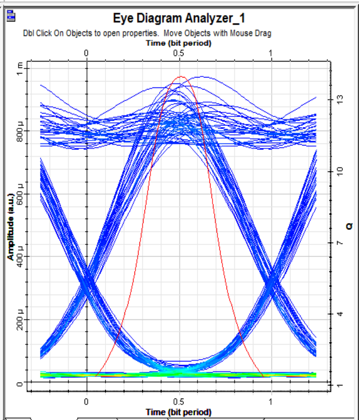
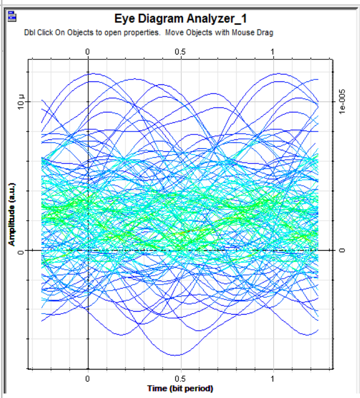
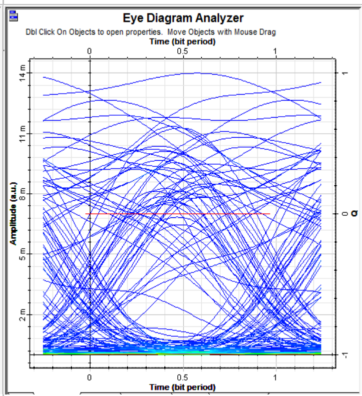
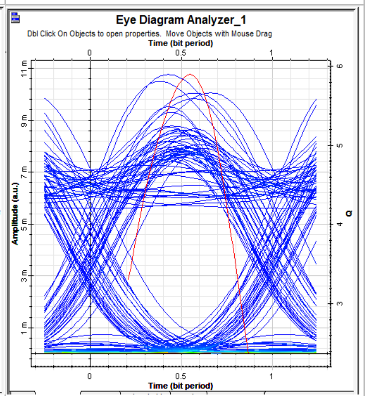
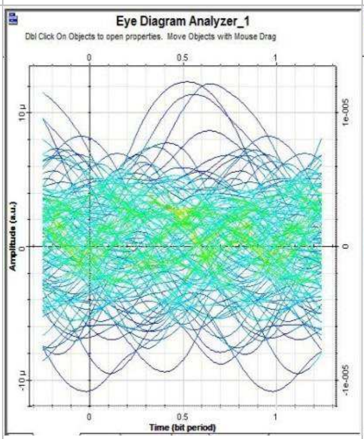
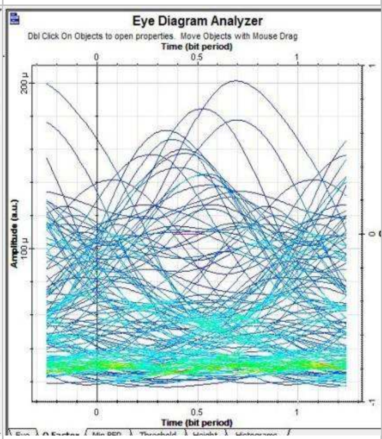
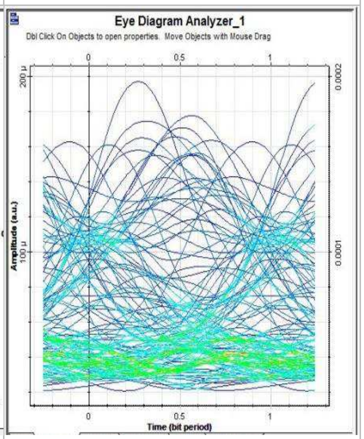
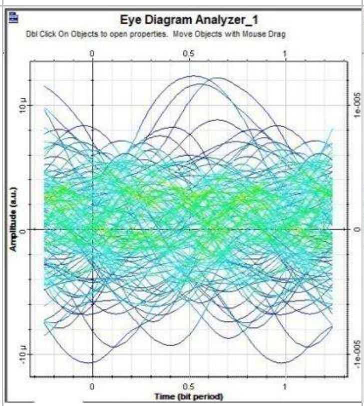
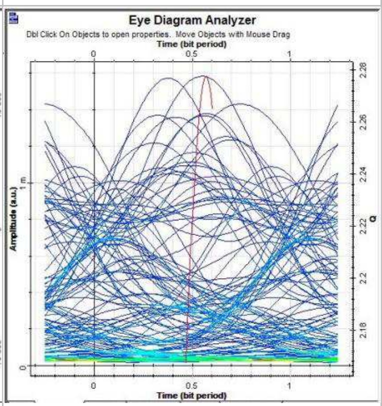
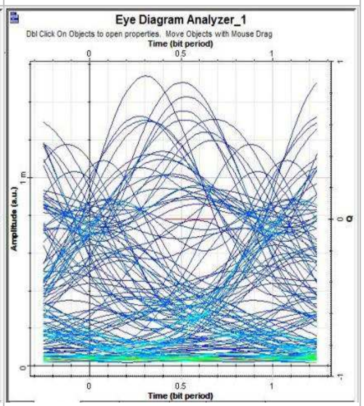
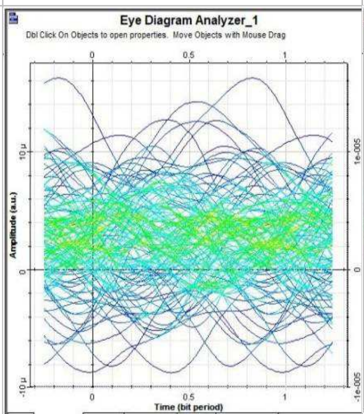
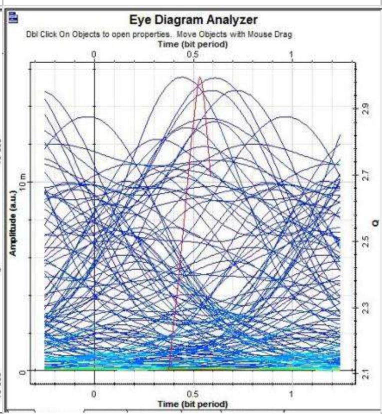
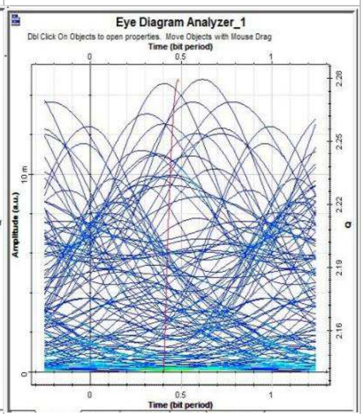
	40 Gbps		
	Withtout Compensation	**Pre-Compensation**	**Post-Compensation**
-10 dBm			
0 dBm			
10 dBm			

Table IV. 12: Eye Diagram Results at 80 Gbps with Different Compensation Techniques.

	80 Gbps		
	Without Compensation	**Pre-Compensation**	**Post-Compensation**
-10 dBm			
0 dBm			
10 dBm			

- **At 10 Gbps**

For all input powers, when compensation measurements have not been taken, it is seen from Table IV.10 that there is a serious distortion of the signal. The receiver cannot determine the received signal and communication lines are not available coming from the cumulative effect of dispersion, which causes the optical signals to be spread with inter-symbol interference and noise model; however, using compensation techniques, from -10 to 0 dBm both pre and post compensations yield a clear open eye diagram, while at P_{in}=0 dBm gives a smooth eye diagram. Beyond 0 dBm the obtained eye diagram at post-compensation is better than the one obtained from pre-compensation.

- **At 40 Gbps**

For conventional case at all input powers, it is observed that system performance is bad resulting from distortion and dispersion effects that causes inter symbol interference phenomenon for the optical signal, whereas using compensation techniques at low input power (P_{in}=10 dBm) gives an open eye diagram; especially, at P_{in}=0 dBm the one of pre-compensation yields a clear open eye diagram with a large eye. Beyond 0 dBm the eye diagram of post-compensation is better than the one of pre-compensation.

- **At 80 Gbps**

From Table IV.12 it is observed that the system performence is bad with and without compensation. This is due to polarization mode dispersion that limits the data rate at high speed transmission systems and non-linear effects that affects the system at high input power.

IV.4.2 Results Discussion of the Effect of the Bit Rate on the System Performence

To study the impact of increasing the bit rate on the system , BER versus input power is plotted for various bit rates 2.5, 10, 20, 30, 40 and 80 Gbps for both pre and post compensations. The obtained graphs are depicted in the following figures.

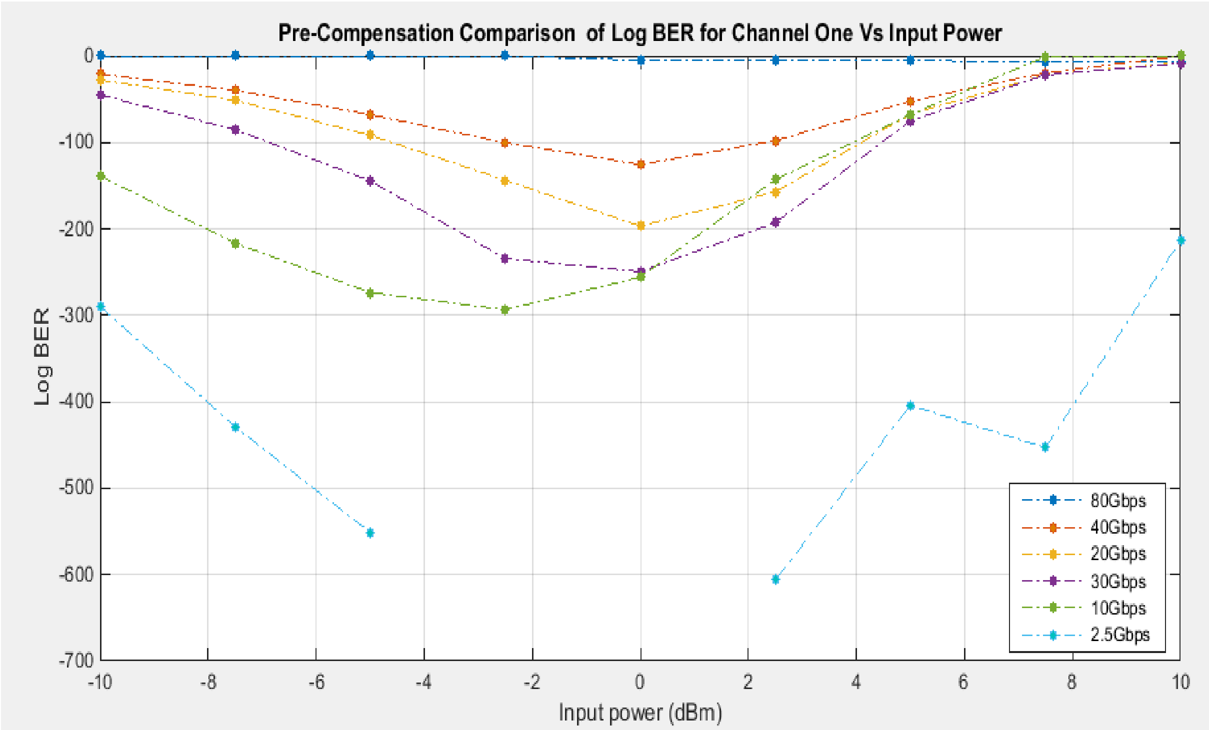


Figure IV. 8: Pre-Compensation Comparison of BER for Channel 1 vs Input Power.

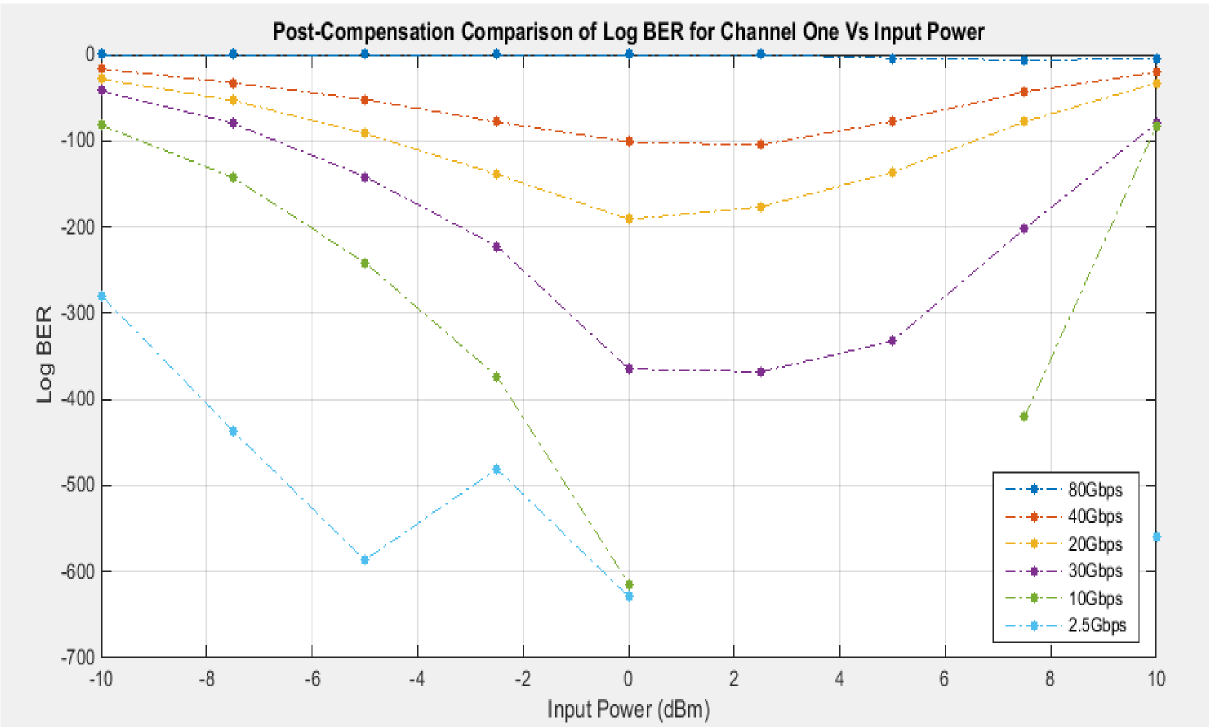


Figure IV. 9: Post-Compensation Comparison of BER for Channel 1 Vs Input Power.

- **Pre-Compensation**

The best system performance is obtained at low bit rate (2.5 Gbps), whereas the worst performance is provided at high bit rate (80 Gbps) which is due to PMD effects. The maximum Q factor is 56.56 and min BER is 0 obtained at P_{in} = 0 dBm for 2.5 Gbps.

- **Post-Compensation**

For high bit rate (80 Gbps) it is observed that the performance is bad. The system operating at 2.5 Gbps has the best performance from -10 to 0 dBm but from 0 to 5.7 dBm the system provides good results at 10 Gbps. Beyond 5.7 dBm the system operating at 2.5 Gbps gives a better results. The maximum Q factor is 56.56 and min BER is 0 obtained at P_{in} = 5 dBm for 10 Gbps.

To simplify the analysis, the above discussions are tabulated below. Table IV.13 gives the value of the input power where each compensation technique is preferable as compared to the other and the best maximum Q-factor and minimum BER obtained for each bit rate value.

Table IV. 13: System Performance Comparison.

Bit Rate	Pre-Compensation			Post-Compensation		
	Input Power (dBm)	Q Factor	BER	Input Power (dBm)	Q Factor	BER
2.5 Gbps	0	56.56	0	7.5	45.76	0
10 Gbps	0	24.04	$3.34e^{-128}$	5	46.46	0
20 Gbps	0	22.13	$5.24e^{-109}$	2.5	26.94	$1.75e^{-160}$
30 Gbps	0	19.61	$3.91e^{-086}$	0	19.33	$1.02e^{-083}$
40 Gbps	0	15.59	$2.97e^{-055}$	2.5	14.21	$2.85e^{-046}$
80 Gbps	7.5	3.011	$1.29e^{-003}$	7.5	2.94	$1.62e^{-003}$

IV.4.3 General Discussion

The results show that when the signal power and the bit rate are very low or very high the system performance degrades, this can be explained by three phenomena:

- At low input power, since the signal is very poor, it is easy to be absorbed by the waveguide material impurities or to escape out of the core even at smaller bending radius, so it gets attenuated rapidely.

- At high input power, nonlinear effects become dominant; mainly, SPM because it is proportional to the transmitted signal power.These effects may be mitigated to some degree by using compensation techniques; however, by increasing the bit rate (above 40Gbps) PMD occurs. The combination of PMD and nonlinear effects results in more complexity in the system, which can not be fixed.

- At high bit rate, PMD severely affects the system, it can be negligible at low data rates, whereas at higher bit-rates (40 Gbps and more) it represents the major limitation in optical transmission systems because it affects the bandwidth and increases the BER in long distance communication, since it is time varying.

IV.5 Conclusion

This chapter was devoted for simulation and results of an eight channel star topology based on OXC and DWDM technology that serves sixty four users. For simplicity, only the first channel is discussed. The simulation was based on Optisystem software operating at 1550 nm window with 100 GHz frequency spacing. Various data rates, input powers and dispersion compensation schemes were investigated in terms of BER and eye diagrams representation to deduce:

- For low input powers, pre-compensation technique is better, whereas for high input powers, post-compensation is preferable.

- In pre-compensation technique, the best input power lies in the range close to 0 dBm, while in post-compensation it lies in the range close to 2.5 dBm.

- At high input power, dispersion compensation is necessary to eliminate the non-linear effects, whereas at high bit rate some sort of PMD compensator is required to filter the adverse effects of Polarization Mode.

Conclusion

Star network topology was investigated to see its application in FTTH and DWDM technologies. This simple topology is node independent; permitting the disconnection of a failed node without affecting the others. It is easy to manage and troubleshoot with a better performance, which make it the ultimate solution in the FTTx market.

In this project, two applications of star topology have been studied. The first is the FTTH technology, which is considered to be an efficient solution for future access network to support the growth traffic of data. The second is DWDM star; this technology is the most adopted in nowadays. Its design is based on an OXC using 2 x 2 couplers, as its performance is analyzed at various input power and different bit rates.

The simulation results have been investigated in terms of BER and eye diagram to analyze the efficiency of DCF pre- and post-compensation techniques when comparing to the conventional case. This study conclusions are summarized as follows:

- Increasing the input power leads to non-linear effects that reduce the performance of communication system in terms of quality and performance.
- Non-linearity effect can be appropriately reduced with the help of DCF.
- At low input powers, pre-DCF technique gives the better compensation compared to the post-compensation but at high input power post-DCF is preferable.
- PMD is the dominant bit rate-limiting effects in long SMFs that should be controlled and compensated.

Future Work

As further work, it is proposed to take into consideration the design of an OXC using optical switches within more complicated topologies such as mesh topology by applying other dispersion techniques like symmetrical DCF, FBG and incorporated DCF with FBG. PMD effects should be taken into account; for this phenomena, compensation should be investigated. Another point to add in this work for high performance is to increase the number of users.

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Appendix A

1. Pulse Generator

Communication system transmit signals by various coding methods either for electrical or for optical. In optical transmission, there are two types of coding the data: The Return-to-Zero (RZ) and Non-Return-to-Zero (NRZ) as illustrated in Figure A.1.

1.1 The Return-to-Zero Format: It explains the line code used in telecommunication signals in which the signal drops to zero among each pulse that represents bit 1 which is shorter than the bit slot.

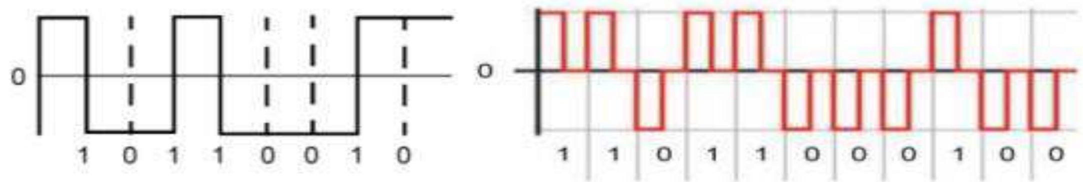
Advantages: The signal is self-clocking, and no need to send different clocks alongside the signal.

Disadvantages: The bandwidth associated with bit stream is big because of time taken during ON-OFF transitions.

1.2 The Non- Return to Zero Format: The pulse remains on throughout, the bit slot and its amplitude do not drop to zero between two or more successive bits. As a result, pulse width varies depending on the bit pattern, whereas it remains the same in the case of RZ format.

Advantages: The bandwidth associated with the bit stream is small and the pulses in NRZ contain more energy than a RZ code.

Disadvantages: It is not inherently a self-clocking indicator, so some other synchronization technique must be used for avoiding fragment slips.



(a) (b)

Figure A.1: Example of Coding Formats in Optical Communication

(a) NRZ data and (b) RZ formats.

2. Optical Modulators

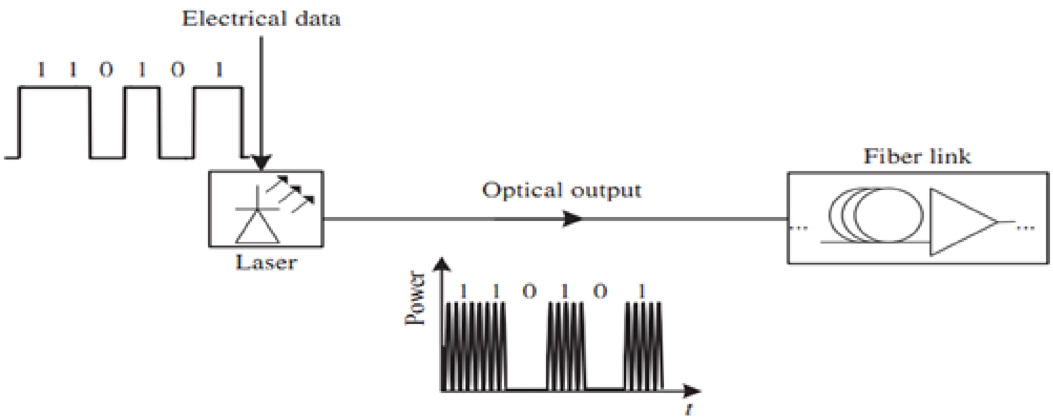
The operation of modulation consists of transferring the data from the electrical to the optical domain. Two strategies, can be used to perform this operation: Direct Modulation and External Modulation.

2.1 Direct Modulation

In this modulation type, the output power of the device depends directly on the input drive current as shown in Figure A.3. When the message signal is bit '0' (bit '1'), the laser is turned OFF (ON) and therefore, the information in the electrical domain is encoded onto the optical domain.

Advantages: This optical modulation is simple. It is cheaper because no complex circuit is involved during modulation process.

Disadvantages: This method is slower compared to indirect or external modulation type (below 3 GHz) .Usually used for transmission systems operating at low bit rates (≤ 10 Gbps) and for short-haul application (<100 km).



.**Figure A.3**: Direct Modulation of a Laser.

2.2 External Modulation

In this method, external device is incorporated to modulate the intensity/phase of the light source. Here, light source is kept ON and external modulator is used which acts as switch/shutter. This switch is controlled by the information to be transmitted. Figure A.4 shows the schematic of a transmitter using external modulators. Widely used external modulators are: The Phase Modulator, The Mach–Zehnder (MZ) Interferometer Modulator and the Electro-absorption (EA) Modulator.

Advantages: It is much faster in processing. It can be used with high power laser devices and can be employed in high speed applications.

Disadvantages: It is more expensive. High frequency RF modulation circuit is required for operation which usually will be complex.

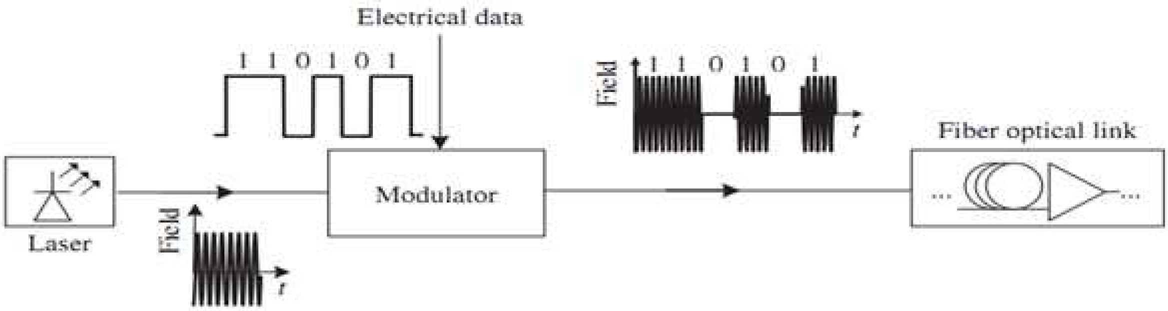


Figure A.4: A Transmitter Using an External Modulator.

3. Single Mode Fibers Types

3.1 Non-Dispersion-Shifted Fiber (ITU-T G.652 Recommendation)

It is also called standard SMF, and it is the most commonly deployed fiber, used in 1310 nm and 1550 nm windows. In the 1310 nm window, it has dispersion close to zero. But in the 1550 nm window, its loss is the smallest, with dispersion of 17 ps/km nm.

When it is used in the 1310 nm window, it is only applicable to the SDH system. However, in the 1550 nm window, it is applicable to both SDH system and DWDM system, requiring dispersion compensation when the single channel rate is over 2.5 Gbps.

3.2. Dispersion-Shifted Fiber (ITU-T G.653 Recommendation)

In Dispersion-Shifted Fiber (DSF), the zero-dispersion wavelength has been shifted from 1310 nm to 1550 nm. Therefore, it usually works in the 1550 nm window, and it is optimized for operating in the region between 1500–1600 nm.

It is applicable to the high-rate and long-distance single-wavelength communication systems. When the DWDM technology is used, serious non-linear FWM problem will occur in zero-dispersion wavelength area, resulting in optical signal attenuation in multiplexing channels and channel crosstalk.

3.3. Nonzero Dispersion-Shifted Fiber (ITU-T G.655 Recommendation)

Nonzero Dispersion-Shifted Fibers (NZDSFs) are SMFs that have chromatic dispersion that is greater than a nonzero value throughout the C band (1500 nm) region.

It is applicable to the high-rate and long-distance optical communication system. In addition, non-zero dispersion suppresses the influence of non-linear FWM over DWDM system. Therefore, this kind of fiber is usually used in the DWDM systems.

4. Optical Wavelength Transmission Bands

Table A.1: Transmission Windows.

Bands	Description	Wavelength Range (nm)
O band	Original	1260-1360
E band	Extended	1360-1460
S band	Short Wavelength	1460-1530
C band	Conventional(“erbium window”)	1530-1565
L band	Long Wavelength	1565-1625
U band	Ultra-long Wavelength	1625-1675

5. Fiber Loss Bands

The attenuation profile illustrate the dependency of light in fiber optics. Modern day fibers (2011) utilizes the C & L bands windows (1550 nm & 1665 nm) because the attenuation of these two wavelength is the lowest.

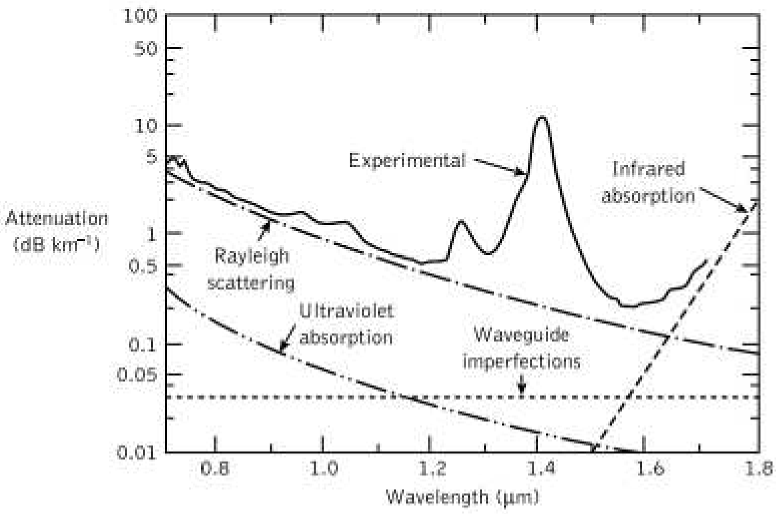


Figure A.6: Loss Spectrum of a Single-Mode Fiber.

The above figure clearly shows the trend in which the scattering loss decreases as the wavelength of operation increases. The contribution of Rayleigh scattering can be reduced to below 0.01 dB/km for wavelengths longer than 3 µm. Silica fibers cannot be used in this wavelength region, since infrared absorption begins to dominate the fiber loss beyond 1.6 µm.

Any material absorbs at certain wavelengths corresponding to the electronic and vibrational resonances associated with specific molecules. For silica ($SiO2$) molecules, electronic resonances occur in the ultraviolet region ($\lambda < 0.4$ µm), whereas vibrational resonances occur in the infrared region ($\lambda > 7$ µm). This loss is a rapidly increasing function of wavelength, so any infrared wavelength gets rapidly attenuated inside glass.

Figure A.6 shows that intrinsic material absorption for silica in the wavelength range 0.8–1.6 µm is below 0.1 dB/km. In fact, it is less than 0.03 dB/km in the 1.3- to 1.6-µm.

During the process of purification glass, some water molecules remain inside glass even after glass has been carefully purified. Water molecules may also get diffused into glass directly from the atmosphere if glass is directly subjected to the atmosphere for prolonged periods of time.

The harmonic of OH^- molecule and its combination tones with silica produce absorption at the 1.39-, 1.24 and 0.95-µm wavelengths. The three spectral peaks seen in Figure A.6 occur near these wavelengths with 10dB/Km, 1.51 dB/Km and 1.98 dB/Km loss respectively.

Appendix B

1. DWDM Topologies

1.1 Point-to-Point Network Topology

Point-to-point networks are characterized by ultra-high channel speeds (10 to 40 Gbps), high signal integrity and reliability, and fast path restoration. In long-haul networks, the distance between transmitter and receiver can be several hundred kilometers, and the number of amplifiers required between end points is typically less than 10. Point-to-point topologies can be implemented with or without add-drop multiplexing that enables the system to drop and add channels along its path. The Figure B.1 depicts a point-to-point network.

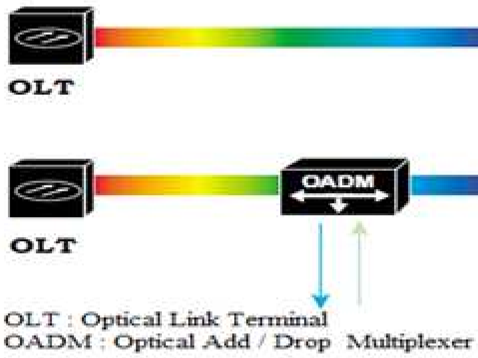


Figure B.1: Point-to-Point Architecture.

1.2 Star Network Topology

Star networks are the simplest form of the network topologies used in LAN architecture. Figure B.2 shows the layout of star topology. It consists of subscribers transceiver nodes which are connected via point to point links to the central node. This topology reduces the chance of network failure by connecting all of the systems to a central node.

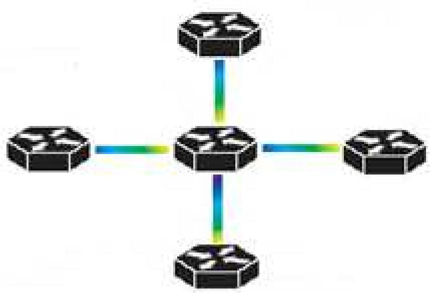


Figure B.5: Star Architecture.

1.3 Ring Network Topology

Rings are the most common architecture found in metropolitan areas and span a few tens of kilometers. Ring configurations consist of one or more DWDM systems, or a hub station with one or more OADM nodes (see Figure B.3). Traffic originates at the hub node, which manages the connectivity with other networks. At the OADM nodes, the selected wavelengths are dropped and added, while the others pass through transparently. In this way, ring architectures allow nodes on the ring to provide access to network elements such as routers, switches, or servers by adding or dropping wavelength channels in the optical domain. With increase in number of OADMs, however, the signal is subject to loss and amplification can be required.

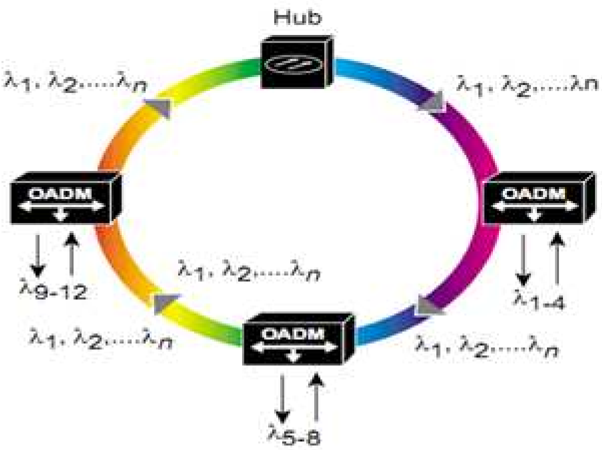


Figure B.3: DWDM Ring Architecture.

1.4 Mesh Network Topology

Mesh architectures are the future of optical networks. As networks evolve, rings and point-to-point architectures will still have a place, but mesh promises to be the most robust topology. This development will be enabled by the introduction of configurable OXCs and switches that will in some cases replace, and in other cases supplement fixed DWDM devices. From a design stand point, there is a graceful evolutionary path available from point-to-point to mesh topologies. By beginning with point-to-point links, equipped with OADM nodes at the outset for flexibility, and subsequently interconnecting them, the network can evolve into a mesh without a complete redesign. Additionally, mesh and ring topologies can be joined by point-to-point links, as shown in Figure B.4 below:

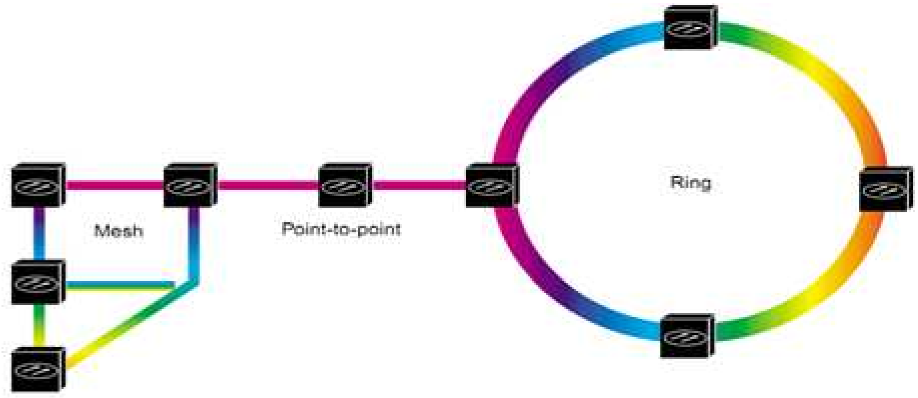


Figure B.4: Mesh, Point-to-Point and Ring Architectures.

2. Multiplexing Techniques in Optical System

Multiplexing is a technique, in which multiple users transmit data over a single channel. It is useful to increase the channel utilization and the transmission capacity. Basic types of multiplexing that are widely utilized by telephone and data service providers over optical circuits include FDM, TDM, CDM and WDM.

2.1 Time Division Multiplexing

In TDM, several low bit rate signals can be multiplexed to form a high bit rate signal by sharing the time slots where each user can transmit data within the provided time slot only. If n number of users with the same pulse width of T_s (seconds) is multiplexed, the pulse width of the multiplexed signals is T/n. In TDM, the MUX and DMUX needs to operate at frequency equal to the total aggregate bitrate, which is n times faster than the bit rate of a single user.

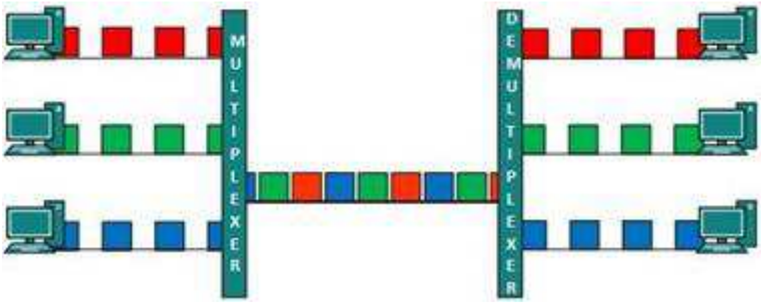


Figure B.5: Time Division Multiplexing.

2.2 Frequency Division Multiplexing

FDM divides the spectrum or carrier bandwidth in logical channels and allocates one user to each channel. Each user can use the channel frequency independently and has exclusive access of it. All channels are divided in such a way that they do not overlap with each other. Channels are separated by guard bands which refers to a frequency which is not used by either channel.

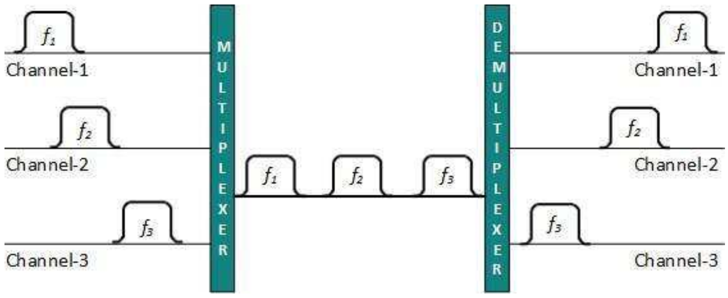


Figure B.6: Frequency Division Multiplexing.

- **Orthogonal Frequency Division Multiplexing**

OFDM essentially is an FDM scheme utilized as a digital multi-carrier modulation method. A large number of closely-spaced orthogonal sub-carriers are used to carry data. The data is divided into several parallel data streams or channels, one for each sub-carrier. Each sub-carrier is modulated with a conventional modulation scheme (such as QAM or PSK) at a low symbol rate, maintaining total data rates similar to conventional single-carrier modulation schemes in the same bandwidth.

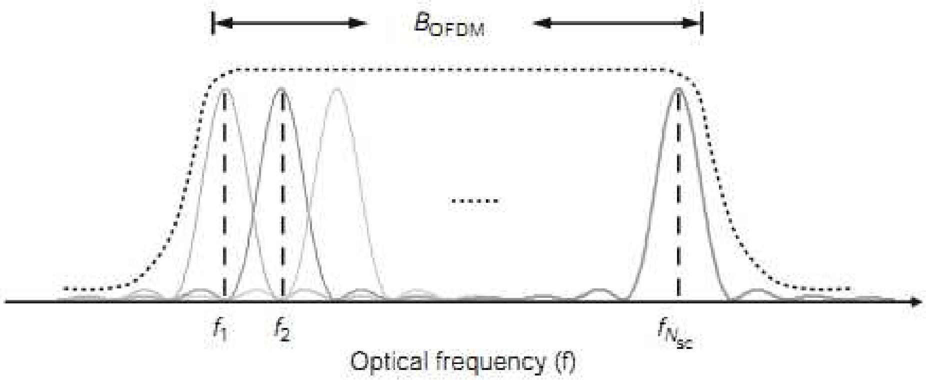


Figure B.7: Orthogonal Frequency Division Multiplexing.

2.3 Code Division Multiplexing

CDM is a network technique in which multiple data signals are combined for simultaneous transmission over a common frequency band where each channel transmits its information (bits) as a coded sequence of pulses. This is achieved by transmitting a time-dependent short series of pulses placed within an allotted time period. Channels that have different codes can transmit on the same fiber.

When CDM is used to o allow multiple users to share a single communication channel, the technology is called Code Division Multiple Access (CDMA).

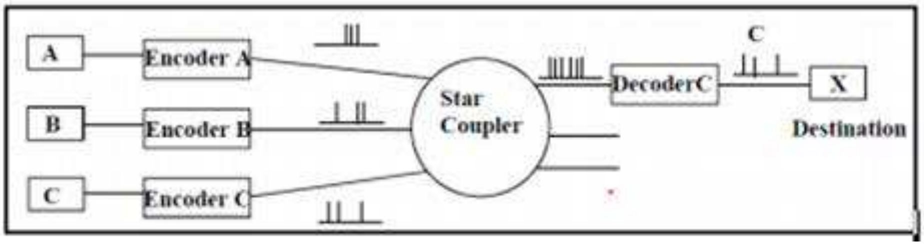


Figure B.8: Code Division Multiplexing.

2.4 Wavelength Division Multiplexing

In WDM systems, different independent users transmit data over a single fiber using different wavelengths. At the transmitter side, N independent users' data is modulated onto n high frequency carriers, each with a unique wavelength (λ). These wavelengths can be spaced based on ITU-T standards. A wavelength multiplexer combines these optical signals and couples them into a single fiber. At the receiving end, a demultiplexer is required to separate the optical signals into appropriate channels.

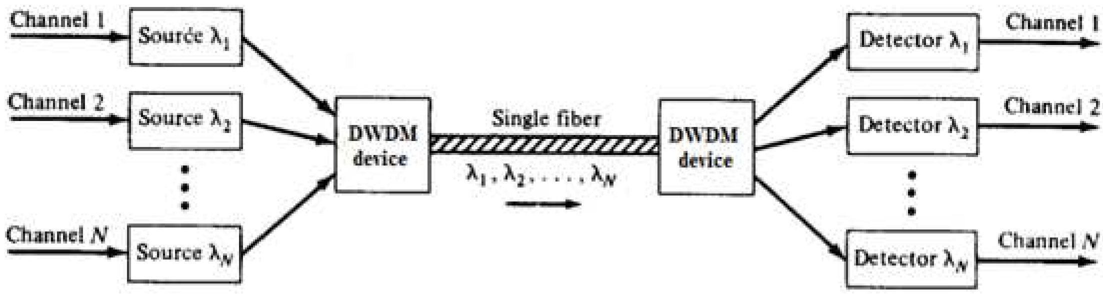


Figure B.9: Wavelength Division Multiplexing in Point to Point Fiber Link.

Appendix C

1. FTTx Networks

FTTx, also called fiber to the x, is a collective term for any broadband network architecture using optical fiber to provide all or part of the local loop used for last mile telecommunications. With different network destinations, FTTx can be categorized into several terminologies, such as FTTH, FTTC, FTTB, FTTDp, etc.

1.1 Fiber To The Home

FTTH, also called "Fiber To The Premises" (FTTP), is the installation and use of optical fiber from a central point directly to individual buildings in order to provide high-speed Internet access. FTTH dramatically increases the connection speeds available to computer users compared with previous technology.

1.2 Fiber To The Building

In FTTB deployment, optical cabling terminates at the buildings. Unlike FTTH which runs the fiber inside the subscriber’s apartment unit, FTTB only reaches the apartment building’s electrical room. The signal is conveyed to the final distance using any non-optical means, including twisted pair, coaxial cable, wireless, or power line communication.

1.3 Fiber To The Curb

FTTC refers to the installation and use of optical fiber cable directly to the curbs near homes or any business environment as a replacement for "plain old telephone service" (POTS). It consists of removing all the telephone lines in the streets and replacing them with optical fiber lines. Such wiring technique would provide extremely high bandwidth and make possible movies-on-demand and online multimedia presentations arriving without noticeable delay.

1.4 Fiber To The Distribution Point

The main objective of FTTDp is to provide much higher data rates than cabinet based VDSL over the existing copper connection to the customer. It terminates at cabinet/node near the group of premises and uses the existing copper network to connect each individual premise.

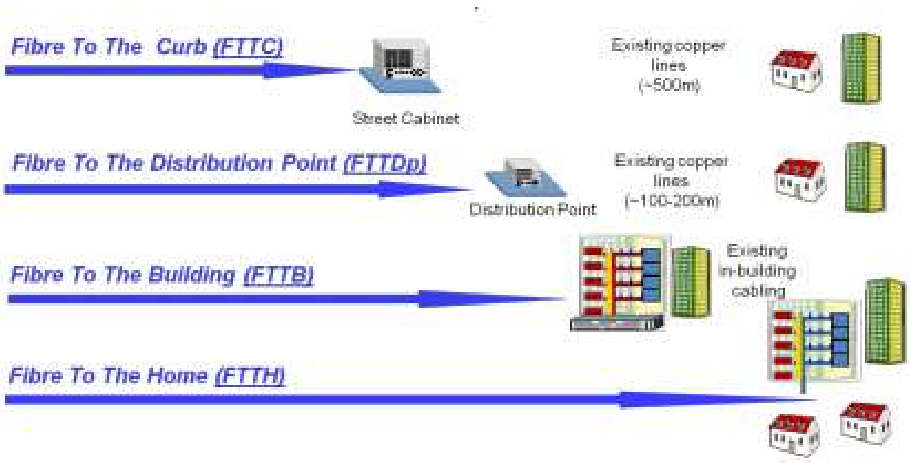


Figure C.1: Different Types of FTTx Networks.

2. The PON Standards Overview

2.1 Gigabit Passive Optical Networks

GPON utilizes optical WDM, so a single fiber could be used for both upstream and downstream data. A laser on a wavelength of 1490 nm transmits downstream data, while upstream data transmits on a wavelength of 1310 nm.

While each ONT gets the full downstream rate of 2.488 Gbits/s, GPON uses a time division multiple access (TDMA) format to allocate a specific time slot to each user. It divides the bandwidth, so each user gets a fraction such as 100 Mbits/s depending on the way the service provider allocates it. The upstream rate is less than the maximum as it is shared with other ONTs in a TDMA scheme. The distance and time delay of each subscriber are determined by the OLT. Then software provides a way to allot timeslots to upstream data for each user. The typical split of a single fiber is 1:32 or 1:64, which means each fiber can serve up to 32 or 64 subscribers. Split ratios up to 1:128 are possible in some systems.

2.2 Ethernet Passive Optical Networks

EPON specifies a similar passive optical network with a range up to 20 km. EPON uses WDM with the same optical frequencies as GPON and TDMA. The raw line data rate is 1.25 Gbits/s in both the upstream and downstream directions.

EPON technology provides bidirectional 1 Gb/s links using 1490 nm wavelength for downstream and 1310 nm wavelength for upstream, with 1550 nm wavelength reserved for future extensions or additional services. EPON is fully compatible with other Ethernet standards, so no encapsulation or conversion is necessary when connecting to Ethernet-based networks on either end. The same Ethernet frame is used with a payload for up to 1518 bytes. As Ethernet is the primary networking technology utilized in local area networks (LAN) and now in metro area networks (MAN), no protocol conversion is needed.

3. Eye Diagram

Eye diagram is a widely used tool for studying the quality and stability of digital communication systems. Figure C.2 shows an example of an eye diagram.

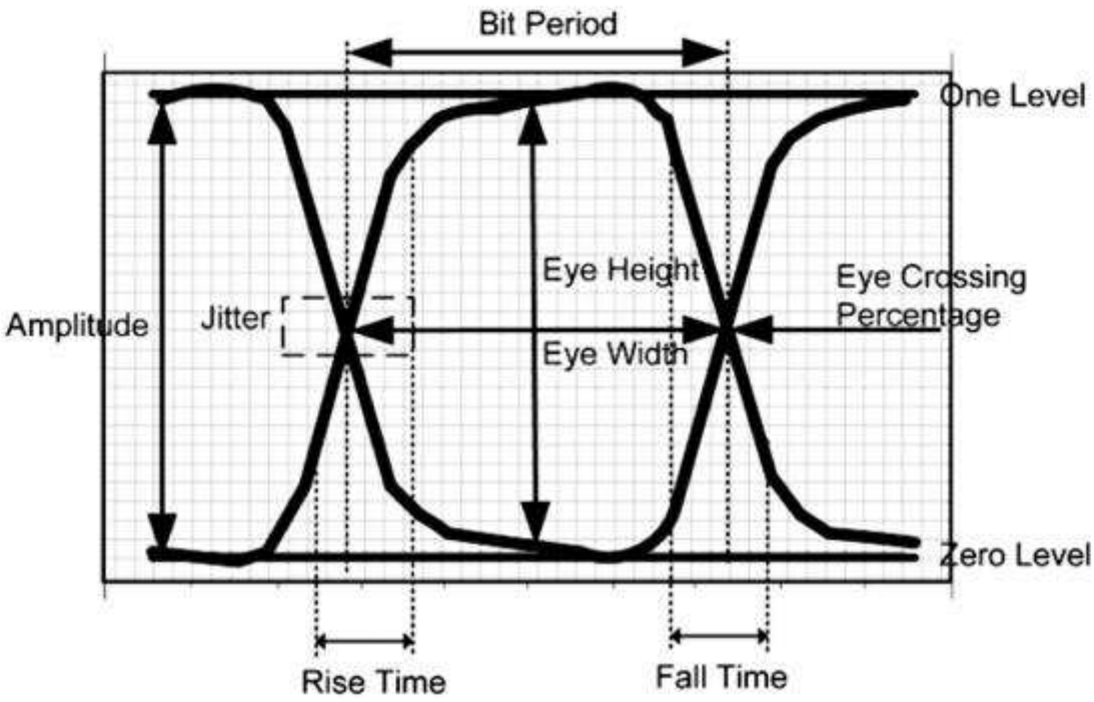


Figure C.2: Eye Diagram Interpretation.

The measurements are defined as follows:

- **One Level**: The one level in an eye pattern is the mean value of a logic one. The actual computed value of the one level comes from the histogram mean value of all the data samples captured inside the middle 20% (40 to 60% points) of the eye period.
- **Zero Level**: The zero level in an eye pattern is the mean value of a logic zero. The zero level is computed from the same 40 to 60% region of the baseline area during the eye period as the one level.

Appendix C

- **Eye Amplitude**: Eye amplitude is the difference between the one and zero levels. The data receiver logic circuits will determines whether a received data bit is a "0" or "1," based on the eye amplitude.
- **Eye Height**: Eye height is a measure of the vertical opening of an eye diagram. An ideal eye opening measurement would be equal to the eye amplitude measurement. For a real eye diagram measurement, noise on the eye will cause the eye to close. As a result, the eye height measurement determines the eye closure due to noise. The signal to noise ratio of the high-speed data signal is also directly indicated by the amount of eye closure.
- **Eye Crossing Percentage**: The crossing level is the mean value of a thin vertical histogram window centered on the crossing point of the eye diagram. The eye crossing percentage is then calculated using the following equation:

$$\text{Eye Crossing } (\%) = \frac{\text{crossing level} - \text{zero level}}{\text{one level} - \text{zero level}} \text{ x } 100$$

- **Bit Period**: The bit period is a measure of the horizontal opening of an eye diagram at the crossing points of the eye and is usually measured in picoseconds for a high speed digital signal. Bit period is the inverse of the data rate($\frac{1}{\text{Bit Rate}}$)
- **Eye Width**: Eye width is a measure of the horizontal opening of an eye diagram. It is calculated by measuring the difference between the statistical mean of the crossing points of the eye.
- **Rise Time**: Rise time is a measure of the mean transition time of the data on the upward slope of an eye diagram. The measurement is typically made at the 20 and 80 percent or 10 and 90% levels of the slope.
- **Fall Time**: Fall time is a measure of the mean transition time of the data on the downward slope of an eye diagram. The measurement is typically made at the 20 and 80 percent or 10 and 90 percent levels of the slope.
- **Jitter**: Jitter is the time deviation from the ideal timing of a data-bit event and is perhaps one of the most important data signal.