RISE TIME BASED QUALITY ANALYSIS OF OPTICAL NETWORKS

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology

In

Communication and signal processing

By

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Department of Electronics & Communication Engineering

National Institute of Technology

Rourkela

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CERTIFICATE

This is to certify that the thesis entitled, “**RISE TIME BASED QUALITY ANALYSIS OF OPTICAL NETWORKS”** submitted by ELDHO BABY in partial fulfillment of the requirements for the award of Master of Technology degree in **Electronics and Communication Engineering** with specialization in “**Communication and Signal Processing**” during session 2012-2013 at National Institute of Technology, Rourkela (Deemed University) and is an authentic work by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other university/institute for the award of any Degree or Diploma.

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I would conclude with my deepest gratitude to my parents and all my loved ones. Their blessings and moral support were always with me during all stages of my academic life. This thesis is a dedication to them who did not forget to keep me in their hearts when I could not be beside them.

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ABSTRACT

The optical network is becoming an important aspect for the present internet communication infrastructure due to good bandwidth provided by optical fiber. The throughputs provided by these networks are of the order of terabits per second, which is tremendously high. It also provides low error rates and low delays, and can also satisfy upcoming applications like supercomputer visualization, medical imaging, and distributed CPU interconnect. In optical networks, lightpath is defined as an all optical WDM channel which establishes a connection between source and destination node by network layer. Whenever the selected path doesn't satisfy the required criteria of either BER or Q-Factor or data rate, the connection will be blocked. Nowadays Wavelength division multiplexing (WDM) is used in optical networks in order to handle the increasing demand of network users. Nowadays, most of the network operators are very strict in terms of Quality of service parameters. The underlying routing systems determine the actual quality of transmission and the concept of Quality of service is based on this system parameters, can be defined as the overall service experience along with customer satisfaction of customer satisfaction.

Lots of works has been done in finding Quality factor early using the effect of several parameters like bandwidth and delay, but this paper focuses mainly on finding quality of transmission using rise time and studies the effect of rise time on transmission data rate and other parameters. Here, we have taken a random network topology with 10 nodes and found out Q-factor for all possible paths and the shortest path for the given source and destination. The analytical model for Q-factor is linked with the rise time of various components in optical communication system and in turn system rise time.

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ACRONYMS

EDFA - Erbium Doped Fiber Amplifier

WDM - Wavelength Division Multiplexing

ASE - Amplified spontaneous emission

ISI - Intersymbol interference

PLL - Phase-lock loop

SONET - Synchronous Optical Network

SDH - Synchronous Digital Hierarchy

SNR - Signal to noise ratio

QoS - Quality of service

BER - Bit error rate

OSNR - Optical signal to noise ratio

Q-Factor – Quality Factor

DWDM - Dense wavelength Division Multiplexing

Chapter 1

Introduction

1.1 Goal and Motivation

1.1.1 Goal

The goal of this thesis is to analyse the effect of rise time of various components of optical communication system on Quality of transmission and several other parameters like transmission data rate and thus optical bandwidth of the system. Using the routing algorithm, all possible paths and the shortest path is calculated for the given source and destination. Simulation results are obtained for Q-factor and BER.

1.1.2 Motivation

The optical network is becoming an important aspect for the present internet communication infrastructure due to the good bandwidth provided by the optical fiber. Optical fiber transmission and communication systems have evolved tremendously over the past few years. Today more than 80 percent of the world's long-distance communication is done with the help of optical fiber cables. The Quality of service characteristics such as bandwidth, delay, and jitter and loss rate influences the routing mechanism in optical networks. Transmission capacity or bandwidth of a channel can be estimated from the time response of the optical system which includes the rise time of the signal in the transmitter, receiver, and dispersion in a fiber. The transmission data rate of a digital fiber optic communication system is limited by the rise time of the various components. Since rise time influences optical bandwidth which indirectly affects data rate, care has to be taken in designing systems so that optical signal passing through them would achieve a better time response. Estimation of Quality of transmission for each path in the network gives a better idea regarding the effect of rise time.

1.2 Literature survey

C.V. Saradhi, S. Subramaniam in [1], describes about the challenges and issues of Physical Layer Impairment Aware Routing (PLIAR) in WDM Optical Networks. This paper shows details regarding PLIs affecting optical communication system. This paper tells that if the received signal quality is not within the receiver sensitivity threshold, the receiver may not be able to correctly detect the optical signal and this may result in high bit-error rates.

Q. Yang.,L. Bo., L.W.Liang.,Y. S. Hoe in [3] tried to explore the problem for on-line VPN design, in particular WDM routed networks. The WDM routed network provides an "optical connection" layer which consists of several lightpath. A lightpath is defined as all-optical connection from the source node to destination node, traversing several intermediate optical wavelength routing nodes.

X. Masip-Bruin., M. Yannuzzi., J. Domingo-Pascual., A. Fonte., M. Curado., E. Monteiro., F. Kuipers.,P. Van Mieghem., S. Avallone., G. Ventre., P. Aranda-Gutirrez., M. Hollick., R. Steinmetz., L. Iannone., K. Salamatian in [4] explains that concept of Quality of Service (QoS) in communication systems is closely related to the network performance of the underlying routing system.This paper defines Quality of Service as ‘collective effect of service performance which determines the degree of satisfaction of a user of the service.’

In paper [5], Dhanya V. V and Santhos Kumar Das discuss about improvement in blocking probably for incoming requests while performing routing by their proposed algorithm and the traditional shortest path algorithm. This paper also explains that each connection request can be specified with a Q-Factor, which is defined in terms of bandwidth and delay associated with the light path.

In paper [6], T. Jiménez, I. de Miguel, J.C. Aguado, R.J. Durán, N. Merayo, N. Fernández, D. Sánchez, P. Fernández, N. Atallah, E.J. Abril, R.M. Lorenzo considered a very simple scenario and developed a Case-Based Reasoning (CBR) method to estimate the Q-factor in optical links with cascades of amplifiers**.** They used a basic analytical model for finding quality factor of optical networks.

In paper [7], Sun-il Kim, Nnamdi Nwanze, Xiaolan J. Zhang and Steven S. Lumetta presented a study of how transmission impairments caused by non-ideal characteristics of network components (such as amplifier spontaneous emission noise and crosstalk) affect the survivability under various QoT aware protection schemes.

In paper [8], Salah Alabady proposed a simulation and best design of an optical single channel in optical communication is presented. Also this paper shows how the fiber dispersion, transmitter and receiver response times, type of signal coding, and spectral width of light source are affect to the performance of the optical fiber communication such as cable length, data rate, BER.

1.3 Thesis Overview

This thesis consists of five chapters which are briefly mentioned below.

Chapter 1: Introduction

Chapter 2: Optical Fiber communication, which contains brief introduction of the optical fiber communication system, its advantage, WDM networks and Optical amplifiers.

Chapter 3: Quality factor and Rise time, which contains basic definitions of Quality factor and rise time and equations showing the relationship them.

Chapter 4: Network design and simulation, which contains the network topology we used for simulation and various simulation results obtained and discussion of the same.

Chapter 5: Conclusion and future work, which contains overall conclusion of work we have done including its future prospective.

Chapter 2

Optical Fiber communication

2.1 Introduction

Transmission of information from one place to another through a medium is known as communication. Many mediums have been using in the past for data transmission. One of these mediums that made a significant effect on data transmission was coaxial-cable system. The first coaxial-cable system, deployed in 1940 [2], was a 3MHz system which could transmit 300 voice channels. Since coaxial-cables mostly suffer from high cable losses and repeater spacing is also very limited, it is expensive for a longer transmission length. And this disadvantage led to the development of microwave communication system. Microwave communication system uses electromagnetic carrier waves in the range of GHz to transmit signals using different carrier modulation techniques. The microwave communication system allows larger repeater spacing but has a drawback of low bit error rate. Then Optical fiber was first developed in the 1970s, which revolutionized the telecommunications provided a good platform for transmission of information at high data rate. Because of greater advantages over the electrical transmission, optical fibers mostly replaced copper wire communications in core networks in the developed countries. Optical communication system use high carrier frequency (~100 THz) in the visible or near-infrared region of the electromagnetic spectrum. Because of its low cable loss, high transmission capacity and bit rate, it became more popular.

2.2 Optical Fiber Communication System

The figure 2.1 [3] shows an optical fiber communication system has three basic components, transmitter, receiver and the transmission path.

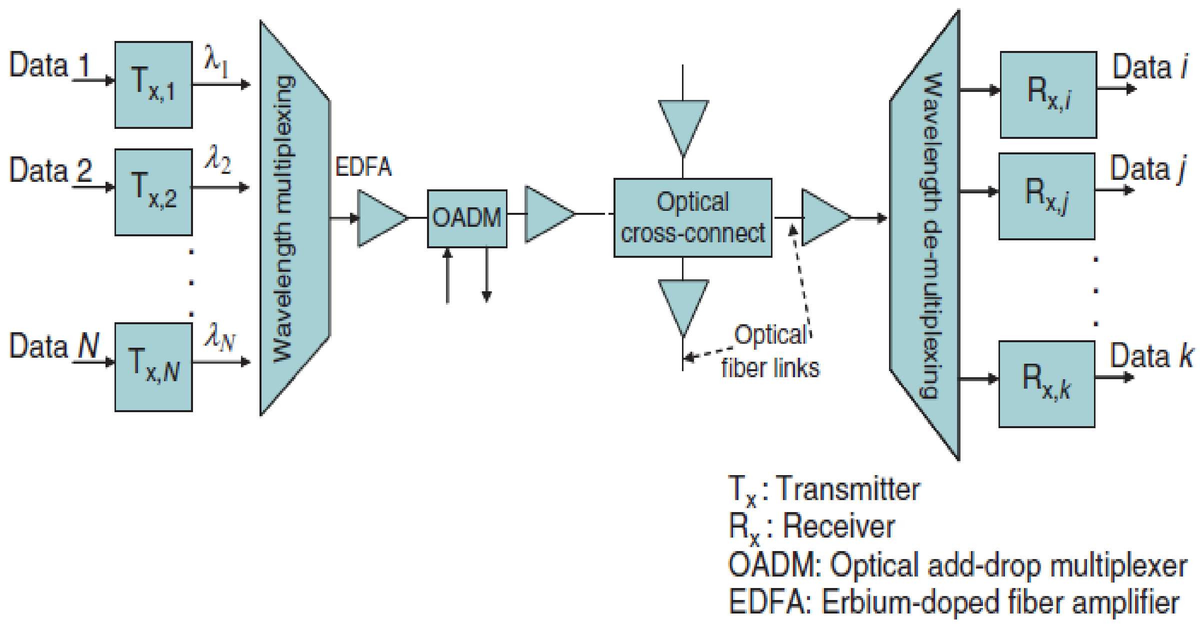

Fig.2.1 Block diagram of Optical fiber communication system

During an end-to-end optical transmission, a signal passes through both electrical and optical signal paths. Optical transmitters are used to perform conversion from electrical to optical domain, whereas to perform conversion in opposite direction (optical to electrical conversion), the optical receivers are used. Since the optical fiber is used as a medium to transport the optical signals from source to destination, it serves as foundation of an optical transmission system. Due to attenuation of the signal during broadcast, optical amplifiers like erbium-doped fiber amplifiers (EDFAs), Raman amplifiers, or parametric amplifiers are used to restore the signal quality. Usually the process of amplification is accompanied with noise addition. A simplest optical transmission system may employ only one wavelength.

An input signal is generated at the transmitter side by a data source. Usually, a laser diode is used an optical source which generates optical light signal at a certain wavelength. Data source combined with optical signal is fed to the modulator and then the resulting modulated pulse signal propagates through the transmission path, optical fiber. The optical signal is detected at the receiver side through an optical detector. Desired output signal is obtained after the detected signal passes through the demodulator. Optical fiber can be described as a flexible thin filament of silica glass that accepts electrical signals as input and converts them to optical signal. An optical fiber carries the optical signal along the fiber length and reconverts the optical signal to electrical signal at the receiver side.

2.3 Advantages of optical fiber communication

1) Cheaper than the conventional wires.
2) Flexible and easy to install.
3) Less affected by fire.
4) Signal can propagate longer transmission distances like 50km or more using optical fiber (Single Mode fiber cables) without the need to regenerate the signal anywhere in-between

5) Do not have speed limitations or bandwidth limitations. Optical fiber cables can support variable speed and bandwidth depending only on optics quality used at both end.
6) It can be easily upgradable for higher speed and high bandwidth.
7) Support duplex communications, bidirectional transmission from Transmitter to Receiver and vice versa.
8) Do not suffer from Electromagnetic Interference as they carry light.
9) Support bandwidth of up to 40Gbps to 100Gbp.
10) The chances of cross talk are very less even if many fibers run alongside each other and hence the signal loss is less compared to Copper Cables.

2.4 Wavelength Division Multiplexing

Optical fiber transmission and communication systems have evolved tremendously over the past few years. Nowadays Wavelength division multiplexing (WDM) is used in optical networks in order to handle the increasing demand of network users [4]. WDM routed networks provides an optical connection layer comprising of several light paths. A light path is defined as an optical connection from the source to destination node through several intermediate routing nodes [5]. In WDM network, the most important issues are routing and wavelength assignment with controlled blocking probability by considering the network cost which is defined as the sum of cost of all the links in the tree.

The optical fiber material offers a large bandwidth of 30THz. Using only one signal of 10MHz is effectively wastage of bandwidth. So in order to use bandwidth efficiently, there are different techniques used like Time Division Multiplexing and Frequency Division

Multiplexing. Since it is very difficult to generate signal of femto seconds, it is difficult to multiplex signal in time domain. Hence frequency division multiplexing is the best technique that can be used to multiplex signals. Wavelength Division Multiplexing Technique has evolved from this concept. Generally, optical fibers can carry multiple light signals of different wavelength simultaneously. Wavelength division multiplexing (WDM) is the technique which allows the optical fiber to carry multiple signals. Hence, it can be said that wavelength division multiplexing is the technique of sending signals of several different wavelengths of light into the fiber simultaneously. In optical fiber communications, wavelength division Multiplexing (WDM) is a technology which multiplexes multiple optical carrier signals on a single optical fiber by using different wavelengths of Laser light to carry different signals. This increases transmission capacity and also helps bi-directional transmission over a single fiber length for transmitter and receiver.

2.4.1 Architecture of a WDM Network

Today’s WDM networks reduce the burden on the underlying electronics by routing data through nodes in the optical domain and are known as second generation optical networks. The basic architecture [6] of such a network is given in the figure 2.2. This network supports variety of client types such as IP routers, ATM switches, SONET/SDH terminals and ADMs and they provides light path to these users. In optical transmission, a light path is defined as a dedicated optical connection between source and destination with a particular wavelength through the entire path (wavelength continuity constrain).

In figure 2.2 we have shown four connections. Lightpath between C-B and E-F does not share any common link, so they can use the same wavelength. On the other hand, the light path between E-F and E-B share a common link and hence they must have to use different wavelengths. Transmission should see that every light path satisfies wavelength continuity constrains and we have assumed that all the nodes do not have wavelength conversion capability.

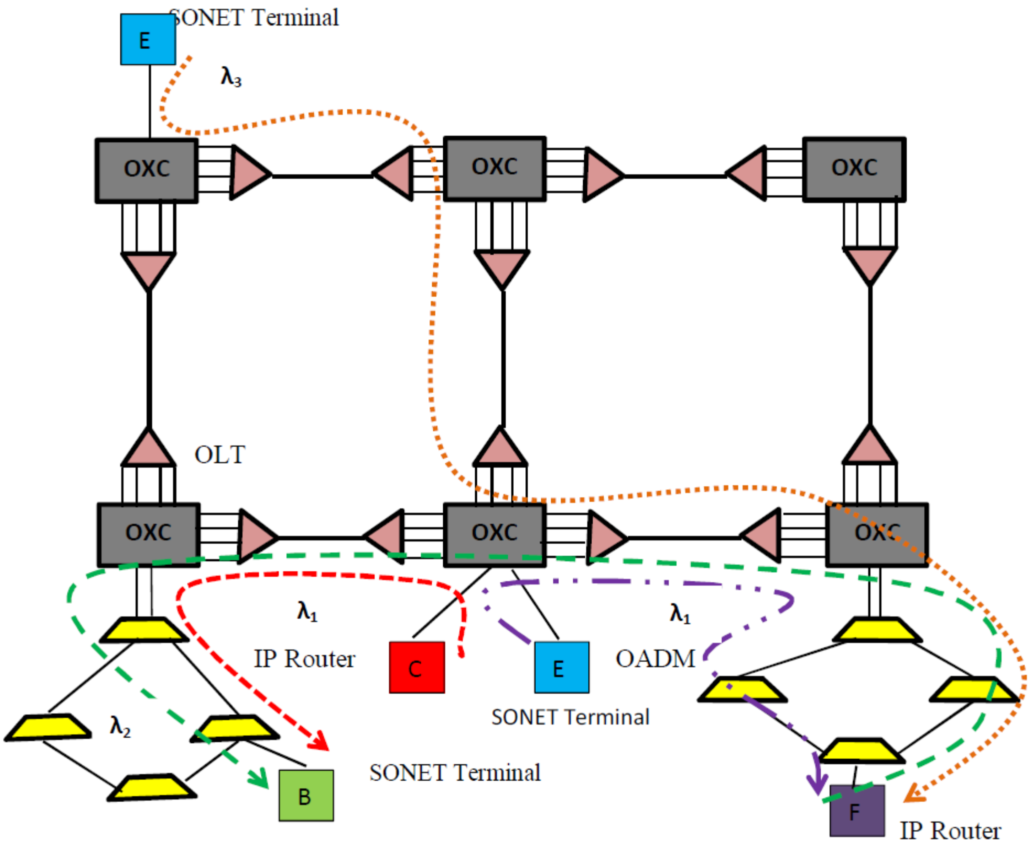

Fig.2.2 A WDM Wavelength Routed Network

2.5 Optical transmitters

Working of a tunable optical transmitter can be understood, if we understand some of the fundamental principles of lasers and how they work. The acronym for word "laser" is light amplification by stimulated emission of radiation. A laser works by the process called stimulated emission, which allows a laser to produce intense high-powered beams of coherent light (light that contains one or more distinct frequencies).

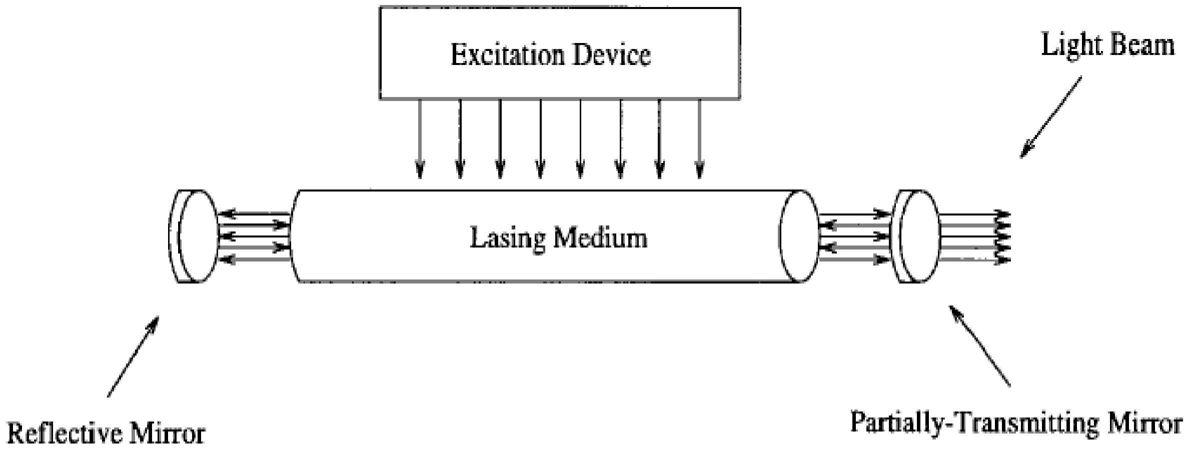

Fig 2.3 The general structure of a laser

Fig. 2.3 displays a general representation of the structure of a laser [7]. Usually a laser consists of two mirrors that form a cavity (the space between the mirrors), a lasing middling, which inhabits the opening, and an excitation device. Current is applied to the lasing medium by the excitation device, which is made of a quasi-stable substance. Electrons in the lasing medium are excited by the applied current, and when an electron in the lasing medium drops back to the ground state, it emits a photon of light. The photon reflects off the mirrors at each end of the cavity and will pass through the medium again.

When a photon passes very closely to an excited electron, stimulated emission occurs. The photon causes electron to release its energy and return to the ground state. By doing so, another photon is released by the electron, with the same direction and coherency (frequency) as the stimulating photon. Photons with frequency as an integral fraction of the cavity length will coherently combine to build up light at the given frequency within the cavity. In between stimulated emission and “normal”, the light at the designated frequency builds intensity until energy is being removed from the medium as fast as it is being inserted. Further stimulated emission can occur and higher intensities of light can be produced, after the mirrors feed the photons back and forth. Since one of the mirrors is partially transmitting, some photons will escape the cavity in the form of a narrowly focused beam of light. The frequency of the emitted light can be adjusted by changing the length of the cavity.

2.5.1 Semiconductor Diode Lasers

Commonly used type of laser for optical networks is the semiconductor diode laser. A semiconductor laser can be simply implemented with a bulk laser diode, which is a p–n junction with mirrored edges perpendicular to the junction (see Fig. 2.4) [7]. The operation of a semiconductor diode can be best described with better understanding of semiconductor physics.

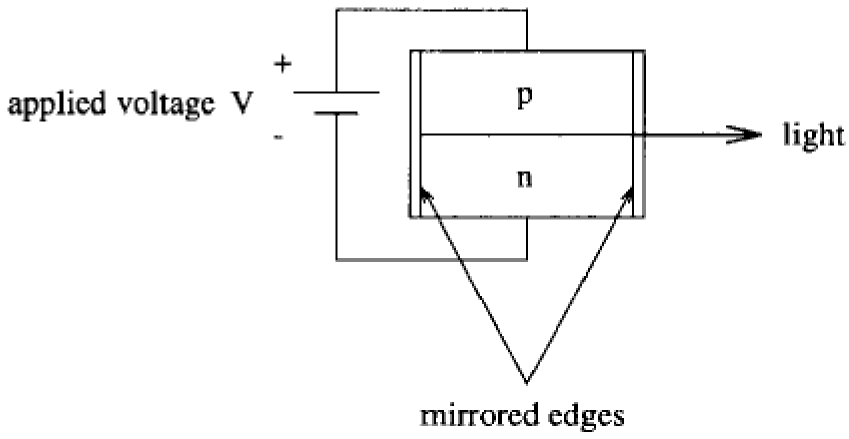

Fig. 2.4 Structure of a semiconductor diode laser

The process of stimulated emission is produced when a voltage is applied across the p-n junction to forward bias the device and cause electrons in the “n” region to combine with holes in the “p” region, resulting in light energy’s being released at a frequency related to the band gap of the device. Light with various ranges of frequencies may be released by using different types of semiconductor materials. The length of the cavity formed by mirrored edges perpendicular to the p-n junction determines the actual frequency of light emitted by the laser.

2.6 Optical receivers

A typical receiver configuration with direct detection is shown in Fig. 2.5 [3]. The main function of the optical receiver which terminates the lightwave path is to convert the signal coming from single-mode fiber from optical to electrical domain and process in such a way that obtained electrical signal can be used to recover the data being transmitted. An optical amplifier is used to preamplify the incoming optical signal and further processed by an optical filter to reduce the level of amplified spontaneous emission (ASE) noise or by wavelength demultiplexer to select a desired wavelength channel. A photodetector converts the optical signal into electrical domain, followed by an electrical postamplifier. In order to compensate with residual intersymbol interference (ISI), an equalizer may be used. A clock recovery circuit provides timing for decision circuit by extracting the clock from the received signal. Normally, the clock recovery circuit is implemented using the phase-lock loop (PLL). Finally, the decision circuit provides the binary sequence to be transmitted by comparing the sampled signal to a predetermined threshold. Whenever received sample is larger than the threshold, the decision circuit goes for bit 1; otherwise it goes for bit 0.

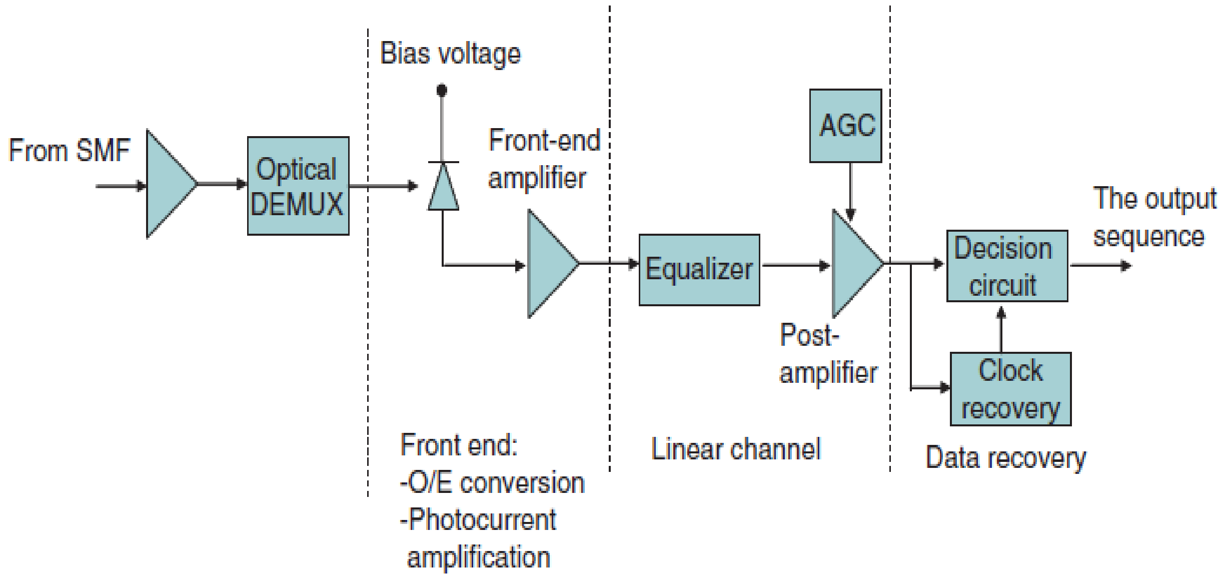

Fig. 2.5 A typical direct detection receiver architecture. O/E optical to electrical and AGC automatic gain control

Before being transmitted over the optical fiber, the optical signal generated by semiconductor laser has to be modulated by information signal. Usually for transmitters operating at 10 Gb/s and above, the semiconductor laser diode (LD) is commonly biased at constant current to provide continuous wave (CW) output, and external modulators are used to impose the information signal to be transmitted. Most common and popular modulators used are electro-optic optical modulators, such as Mach–Zehnder modulator. Fig. 2.6 [3] illustrates the principle of the external modulator.

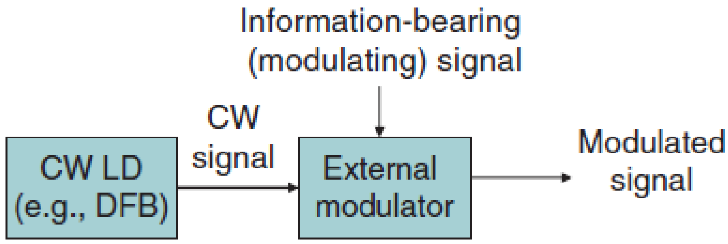

Fig. 2.6 An illustration of external modulation principle. DFB distributed feedback laser

2.7 Optical amplifiers

Both long-haul and local lightwave networks can benefit from optical amplifiers even though an optical signal can propagate a long distance before it needs amplification. All-optical amplification differs from optoelectronic amplification in a way that it may act only to boost the power of a signal, not to restore the shape or timing of the signal. This is known as 1R (regeneration) type of amplification, and provides total data transparency (the amplification process is independent of the signal's modulation format). Nowadays, 1R amplification emerges as the choice for the transparent all-optical networks. Today's digital networks mostly refers to Synchronous Optical Network (SONET) and Synchronous Digital Hierarchy (SDH)] use the optical fiber only as a transmission medium and the optical signals are amplified by first converting the information stream into an electronic data signal and then retransmitting the signal optically. This type of amplification method is commonly referred to as 3R (regeneration, reshaping, and reclocking). The original pulse shape of each bit is reproduced from the signal by reshaping it, eliminating much of the noise. Reshaping can be primarily applied to digitally modulated signals but in some cases, it can also be applied to analog signals. Synchronization of the signal to its original bit timing pattern and bit rate is done by reclocking of the signal. Reclocking can be applied only to digitally modulated signals. Another method of amplification used is 2R (regeneration and reshaping), in which the optical signal is converted to an electronic signal, which is then used to modulate a laser directly.

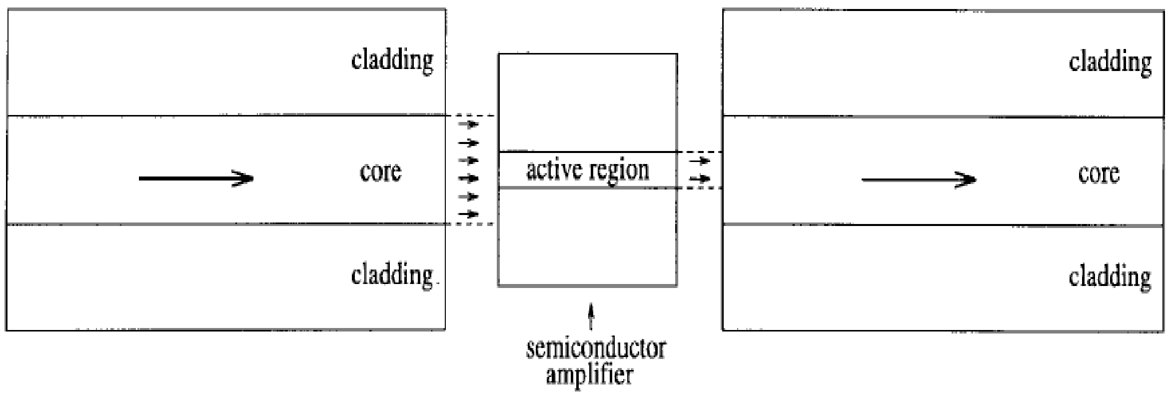

Fig. 2.7 A semiconductor optical amplifier.

Moreover in a WDM system, each wavelength has to be separated before being amplified electronically, and then recombined before being retransmitted. In order to avoid the use of optical multiplexers and demultiplexers in amplifiers, optical amplifiers must boost the strength of optical signals without first converting them to electrical signals. Main disadvantage is that noise, as well as the signal, will be amplified.

2.7.1 Optical Amplifier Characteristics

Some of the basic parameters which have to be considered in an optical amplifier are gain, gain bandwidth, gain saturation, polarization sensitivity, and amplifier noise [7].

Gain is usually measured as the ratio of the output power of a signal to its input power. Sometimes, *gain efficiency* is also used to describe amplifiers, which is nothing but processes the gain as a function of input power in dB/mW.

The *gain bandwidth* of an amplifier refers to the range of frequencies or wavelengths over which the amplifier is effective. The gain bandwidth limits the number of wavelengths available for a given channel spacing in a network.

The *gain saturation* point of an amplifier is the value of output power at which the output power no longer increases with an increase in the input power. The carriers (electrons) in the amplifier are unable to output any additional light energy when the input power is increased beyond a certain value.

The *saturation power* is normally defined as the output power at which there is a 3-dB reduction in the ratio of output power to input power (the small-signal gain) is known as.

Polarization sensitivity refers to the dependence of the gain on the polarization of the signal. The sensitivity is usually measured in dB and defined as the gain difference between the TE and TM polarizations.

The dominant source of noise in an optical amplifier is amplified spontaneous emission (ASE), which arises from the spontaneous emission of photons in the active region of the amplifier (see Fig. 2.7). Basically, the amount of noise generated by the amplifier depends on factors such as the amplifier gain spectrum, the noise bandwidth, and the population inversion parameter, which specifies the degree of population inversion that has been achieved between two energy levels. When multiple amplifiers are cascaded, amplifier noise is especially a problem.

2.8 General applications of optical amplifier

2.8.1 In-line Optical Amplifiers

Usually the signal goes through loss due to attenuation in a single mode optical fiber. Hence regeneration of the signal and its amplification needs to be done after a certain interval of time. Inline optical amplifier can be used to compensate attenuation loss and to increase the distance between regenerative repeaters.

2.8.2 Preamplifier

Commonly, an optical amplifier is used as a front-end preamplifier before an optical receiver. In order to minimize the SNR degradation, the weak optical signals can be amplified by the preamplifier and also preamplifier shows high gain and better bandwidth.

2.8.3 Power Amplifier

Boosting of the signals is done by the power or booster amplifiers placed just after the transmitter. Depending on the amplifier gain and fiber loss, the transmission distance can be increased by 10-100 km. Fig. 2.8 shows the diagram for Preamplifier, inline amplifier and post amplifier is given.

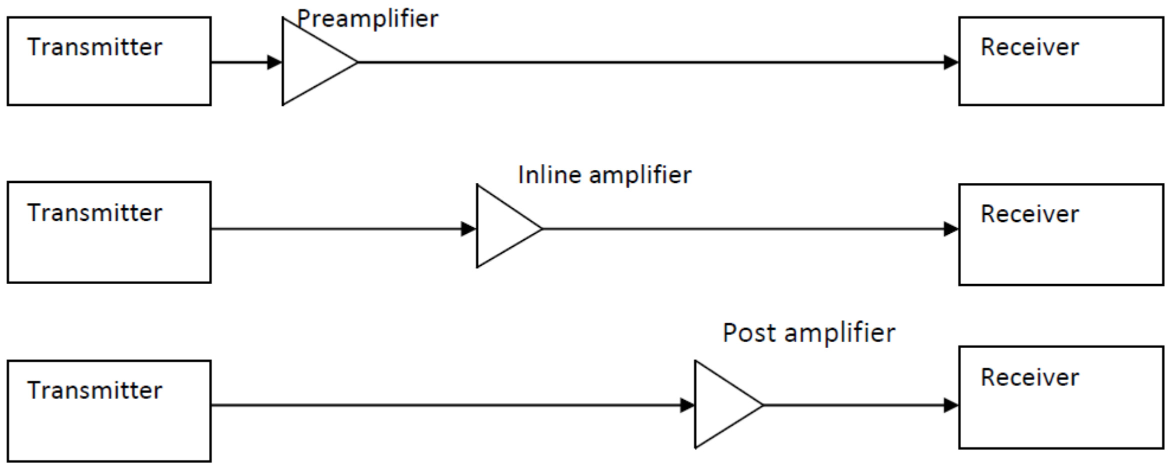

Fig 2.8 Block Diagram of different application of optical amplifier

2.9 Erbium doped fiber amplifier (EDFA)

When a conventional silica fiber is heavily doped with active erbium ions as the gain medium, it is known as Erbium doped fiber. Erbium ions (Er3+) are suitable for the optical amplification since they are having the optical fluorescent properties. Typical diagram for EDFA is shown in the Fig. 2.9 [7]. The two wavelength widows C-Band (1530nm-1560nm) and L-Band (1560nm-1600nm) are used practically. EDFA is very useful in wavelength division multiplexing for amplification since they can amplify a wide wavelength range (1500nm-1600nm) simultaneously. The basic functioning of EDFA says that when an optical signal such as with 1550nm wavelength signal enters the EDFA from input, the signal is combined with a 980nm or 1480nm pump laser using a wavelength division multiplexer device. The input signal and pump laser signal pass through fiber doped with erbium ions. Amplification of the 1550nm signal takes place through interaction with doped erbium ions. Usually, lasers with a wavelength of either 980 or 1480 nm are used to pump most of the erbium-doped fiber amplifiers (EDFA's). Gain efficiencies of around 10 dB/mW have shown by the 980-nm pump wavelength, while the 1480-nm pump wavelength provides efficiencies of around 5 dB/mW. Typical gains are on the order of 25 dB.

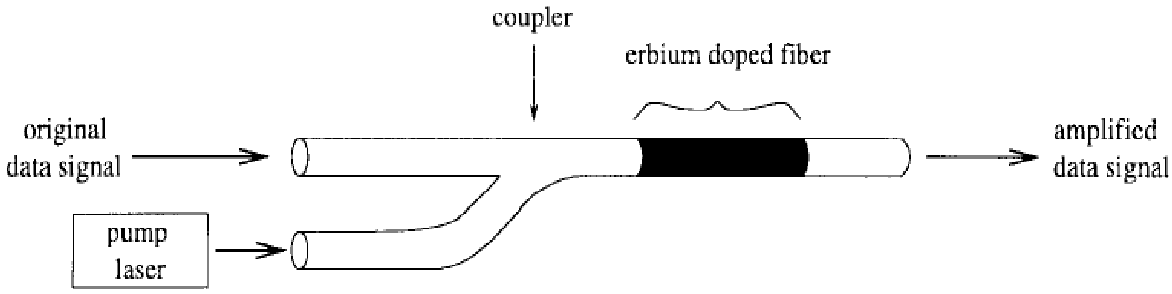

Fig. 2.9.EDFA

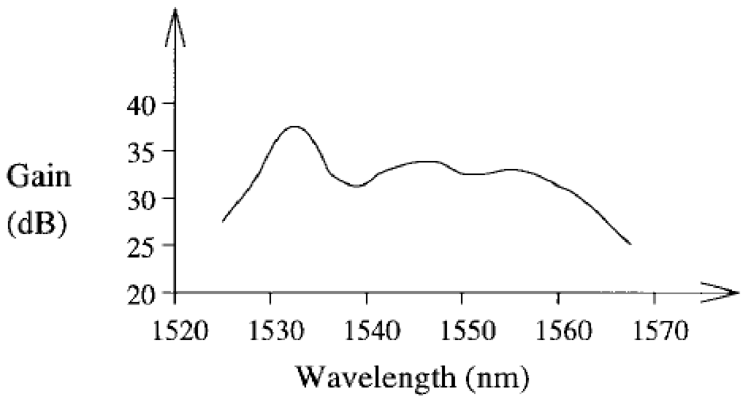

Fig. 2.10 The gain spectrum of an EDFA with input power = - 40 dBm.

EDFA's have been shown to achieve gains of up to 51 dB experimentally with their maximum gain limited by internal Rayleigh backscattering where some of the light energy of the signal is scattered in the fiber and focussed back toward the signal source [8]. The 3-dB gain bandwidth for the EDFA is around 35 nm (see Fig. 2.10) [9], and the gain saturation power is around 10 dBm.

Chapter 3

Quality factor and Rise time

3.1 Introduction

The underlying routing systems determine the actual quality of transmission and the concept of Quality of service is based on this system parameters, can be defined as the overall service experience along with customer satisfaction of customer satisfaction [10]. The network can be defined in terms of the QoS metrics or cost metrics such as BER, OSNR, data rate, Q-factor. While routing, the provisioning is done in such a way that the selected route should satisfy the QoS requirement of the client. Quality factor (Q-Factor) is defined in terms of the bandwidth and delay associated with the fiber in the path for each light path [11].

We have to make sure that system is performing normally without troublesome and is able to transport information at high data rate. In certain manner, we can say that power budget and rise time budget can roughly influence the transmission distance and the bit rate in communication system. Transmission capacity or bandwidth of a channel can be estimated from the time response of the optical system which includes the rise time of the signal in the transmitter, receiver, and dispersion in a fiber [12]. Fiber dispersion may be intramodal or intermodal dispersion and dispersion varies depending upon the link distance.

The system time response t_s is the square root of the sum of the squares of transmitter rise time, receiver rise time, laser diode rise time, photodiode rise time and the pulse spreading caused by fiber dispersion. Transmitter and receiver rise time and full times are listed on data sheets, fiber response times must be calculated from the fiber length, the characteristic dispersion per unit length, and the source spectral width. Except the fiber dispersion which is expressed in picosecond, rest of the rise times is usually expressed in nanosecond. Modal, chromatic (is the sum of material and waveguide dispersion), and polarization-mode dispersion are mainly the available three categories of dispersion.

3.2 Q-Factor

The Q-Factor is a sign of the quality of transmission, which can be derived from the following expression [13].

$$Q = \frac{2*OSNR*\sqrt{B_o/B_e}}{1+\sqrt{(1+4OSNR)}} \quad (3.1)$$

$$OSNR = \frac{Pt_x}{2*n_{sp}*h*f_c*(G-1)B_0*N_{amp}} \quad (3.2)$$

Where OSNR is optical signal to noise ratio, B_0 is optical bandwidth, B_e is electrical bandwidth, Pt_x is transmitted power, n_{sp} is spontaneous emission factor, h is Planck's constant, f_c is carrier frequency, G is gain of the amplifier, N_{amp} is number of optical amplifiers cascaded between links.

The client's requirement is usually defined as Quality of Service and the light path routing has to be done in such a way that it assures the Q-Factor requirement of the client and also considering the availability of resources in the network. The maximum value of Q-Factor is the optimum requirement for the connection request. The combined effect of service performance which determines the degree of satisfaction of user of the service is called Quality of Service. QoS characteristics such as bandwidth, delay, jitter and loss rate are used to support routing in optical network include. QF is defined in terms of the bandwidth and delay connected with the fiber in the path for each light path in the network. Bandwidth is mainly affected by the length of the link and dispersion effect in the fiber link. Moreover, delay depends on the wavelength allotted for the light path.

3.2.1 OSNR and BER

Different effects that may degrade the signal during modulation, propagation, and detection processes, influences the optical transmission system design. The ratio between signal power and noise power at the decision point is known as the received signal-to-noise ratio (SNR) which also determines the transmission quality. The minimum received optical power needed to keep SNR at the specified level is called receiver sensitivity which is also related to SNR. Bit-error rate (BER) is defined as the ratio of error bits to total number of transmitted bits at the verdict point and is commonly used as a figure of merit in digital optical communications.

$$\text{BER} \approx \frac{exp^{\frac{-Q^2}{2}}}{Q*\sqrt{2*\pi}} \qquad (3.3)$$

Where Q is quality factor and (3.3) indicates that higher value of Q-Factor results in a lower value for BER [14].

Basically, from the system engineering point of view, we can observe that there are three types of parameters include (1) optical signal parameters that determine the signal level, (2) the optical noise parameters that determine the BER, and (3) the impairment parameters that determine the power margin to be assigned to pay off for their impact. The signal level parameters like optical transmitter output power, extinction ratio, optical amplification gain, and photodiode responsivity define the optical signal.

3.2.2 Electrical and Optical Bandwidth

Electrical bandwidth (BWe) is defined as the frequency at which the ratio current out/current in (Iout/Iin) gets reduced to 0.707. (Normally, electrical bandwidth is used to specify the analog systems.)

Optical bandwidth (BWo) is the frequency at which the ratio power out/power in (Pout/Pin) gets reduced to 0.5. Since Pin and Pout are directly proportional to Iin and Iout, the half-power point is equivalent to the half-current point. This results in a BWo that is larger than the BWe which can be expressed as [15].

$$BWe = 0.707 * BWo \tag{3.4}$$

3.3 Rise time

In electronics, rise time is the time taken by a signal to change from a definite low value to a indicated high value and is usually used while describing a voltage or current step function. Typically saying, the range of these values is 10% and 90% of the step height in case of analog electronics. But according to Levine, rise time is defined in control theory applications, as "the time required for the response of the system to rise from x% to y% of its ultimate value". Basically, the variation is 0%-100% for underdamped second order systems, 5%-95% for critically damped and 10%-90% for overdamped.

Transmission of the envisioned bit at high bit rate and effectively is important while designing systems. In assured manner, we can say that can the transmission distance and the bit rate in communication system are coarsely influenced by power budget and rise time budget. Transmission capacity or bandwidth of a channel can be estimated from the time response of the optical system which includes the rise time of the signal in the transmitter, receiver, and dispersion in a fiber [12]. The system time response t_s is the square root of the sum of the squares of transmitter rise time, receiver rise time, laser diode rise time, photodiode rise time and the pulse spreading caused by fiber dispersion. Transmitter and receiver rise time and full times are listed on data sheets, fiber response times must be calculated from the fiber length, the characteristic dispersion per unit length, and the source spectral width. Except the fiber dispersion which is expressed in picosecond, rest of the rise times is usually expressed in nanosecond. Modal, chromatic (is the sum of material and waveguide dispersion), and polarization-mode dispersion are mainly the available three categories of dispersion.

The transmission data rate of a digital fiber optic communication system is limited by the rise time of the numerous constituents, mostly by the amplifiers and LEDs, and also by the dispersion of the fiber. The combined effect of all the components may influence the bandwidth of the system. The rise time t_s and system bandwidth BW are related by [15].

$$\mathrm{B}W_s = 0.35/t_s \tag{3.5}$$

The required system rise time is determined by using this equation. The suitable components are then carefully chosen to meet the system rise time necessities. The connection between total system rise time t_s and component rise time t_r can be expressed as [15]

$$t_s = (t_{r1}^2 + t_{r2}^2 + \cdots)^{\frac{1}{2}} \tag{3.6}$$

where t_s is the total system rise time and t_{r1} , t_{r2} ... are the rise times associated with the number of components.

The rise time components can be of five groups such as

1. Transmitting circuits (t_{tc})

2. LED or laser (t_l)

3. Fiber dispersion (t_f)

4. Photodiode (t_{ph}), and

5. Receiver circuits (t_{rc})

Now (3.6) be expressed as

$$t_s = \sqrt{(t_{tc}^2 + t_l^2 + t_f^2 + t_{ph}^2 + t_{rc}^2)} \qquad (3.7)$$

By replacing t_s in (3.5), the system bandwidth can be expressed as

$$\mathrm{B}W_s = \frac{0.35}{\sqrt{(t_{tc}^2+t_l^2 +t_f^2 +t_{ph}^2 +t_{rc}^2)}} \qquad (3.8)$$

3.3.1 Rise time and Data rate

The transmission data rate of a digital fiber optic communication system is limited by the rise time of the numerous constituents, mostly by the amplifiers and LEDs, and also by the dispersion of the fiber. Here by data rate, we are indirectly referring to optical bandwidth of the communication system [12].

The variation has been shown in Fig. 3.1 for NRZ and RZ signalling used for transmission of data. For NRZ signalling, power applied will be for the entire time period but RZ signalling, power is applied only for a fraction of time period hence time period for RZ signalling will be less compared to NRZ signalling.

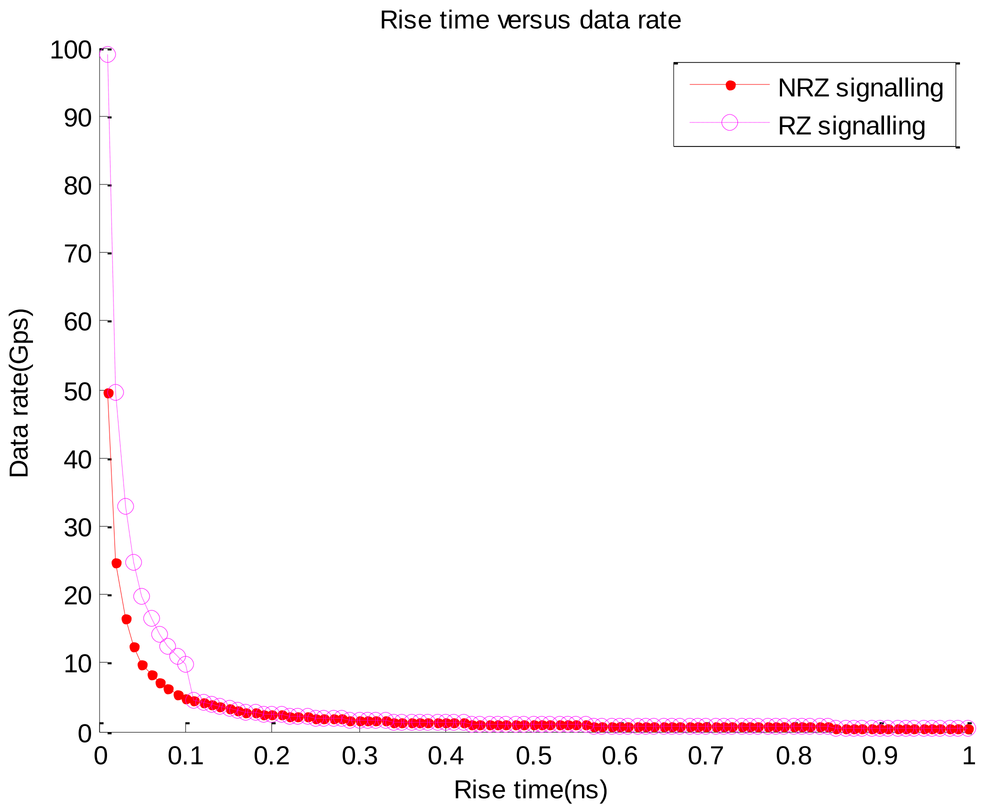

Fig. 3.1 Data rate variation with rise time

3.4 Dispersion

There are usually three types of dispersion found in optical fibers; modal, chromatic (is the sum of material and waveguide dispersion), and polarization-mode dispersion. In single mode fiber, chromatic dispersion and polarization-mode dispersion are significant but modal dispersion is zero. But in case of multimode fibers, only model and chromatic dispersion are considered since polarization mode dispersion is insignificant. In Single mode fibers, only chromatic and polarization mode dispersion is considered since they do not suffer modal dispersion.

3.4.1 Chromatic Dispersion (CD)

The degradation of an optical signal caused by the various spectral components traveling at their own different velocities is called dispersion. CD causes an optical pulse to broaden such that it spreads into the time slots of the other pulses. It is considered as the most serious linear impairment for systems operating at bit-rates higher than 2.5 Gb/s. CD depends on bit-rate, modulation format, type of fiber, and the use of dispersion compensation fiber (DCF) modules. The total dispersion at the end of a light path is the sum of dispersions on each fiber-link of the considered light path, where the dispersion on a fiber-link is the sum of dispersions on the fiber-spans that compose the link [20].

3.4.2 Polarization Mode Dispersion (PMD)

Along the fiber span, the fiber may be subjected to environmental stress such as local heating or movement, also it could be non-circular and may contain impurities. These abnormalities cause complications to an optical pulse along its path. These complications may cause different polarizations which may result in optical signal to travel with different group velocities and cause pulse spread in the frequency domain, known as PMD. By shortening the optical transmission distance by placing OEO regenerators between two optical nodes, PMD induced problems can be reduced. However, the transmission link must first be demultiplexed, then regenerated, and then multiplexed again, as most long-haul DWDM systems are multi-wavelength and is a very expensive operation. Use of dispersion compensation modules (DCM) at optical add/drop multiplexers (OADMs), optical crossconnects (OXCs), or amplifier sites compensate for accumulated PMD on an optical path [16-19].

3.4.3 Modal dispersion

In multimode fibers, modal dispersion becomes prime. While drifting down the fiber, different modes in the fiber take different path and so different length. Another factor is that in multimode fiber each mode may be associated with different propagation constant. Pulse spreading usually occurs due to the time delay between different modes caused by modal dispersion. For the same size, the modal dispersion of graded index fiber is less compared to step index fiber [19].

3.4.4 Waveguide dispersion

The relationship between the physical dimensions of the waveguide and the light pulse causes a type of dispersion called waveguide dispersion. Waveguide dispersion mainly affects single mode fiber. The fact that some light travels, about 20% of total signal power, in the fiber cladding compared to most light travels in the fiber core, causes this dispersion. In optical fibers, thus the propagation constant of a mode can be defined as a function of a/λ, where a represents the core radius of fiber and λ for the wavelength of the optical signal. For a fiber, wavelength dispersion can be even present in which core cladding refractive indexes are independent of wavelength [21].

Chapter 4

Network design and simulation

4.1 Optical network architecture

Fig 4.1 shows a typical optical network. Optical network can be divided into three truncations representing the core network, the edge network, and the access network [21]. By means of submarine transmission systems, the long-haul core network communicates with big cities, major communications hubs, and even with different continents. The core networks are usually called as wide area networks (WANs). The edge optical networks are commonly known as metropolitan area networks (MANs) or local exchange carrier networks installed within smaller topographical areas. The access networks provide the last-mile access or the bandwidth distribution to the individual end-users and represent marginal part of optical network. Local area networks (LANs) and distribution networks are the common access networks. Different physical network topologies are used in optical networks such as mesh network (often present in core networks), ring network (in edge networks), and star networks (commonly used in access networks).

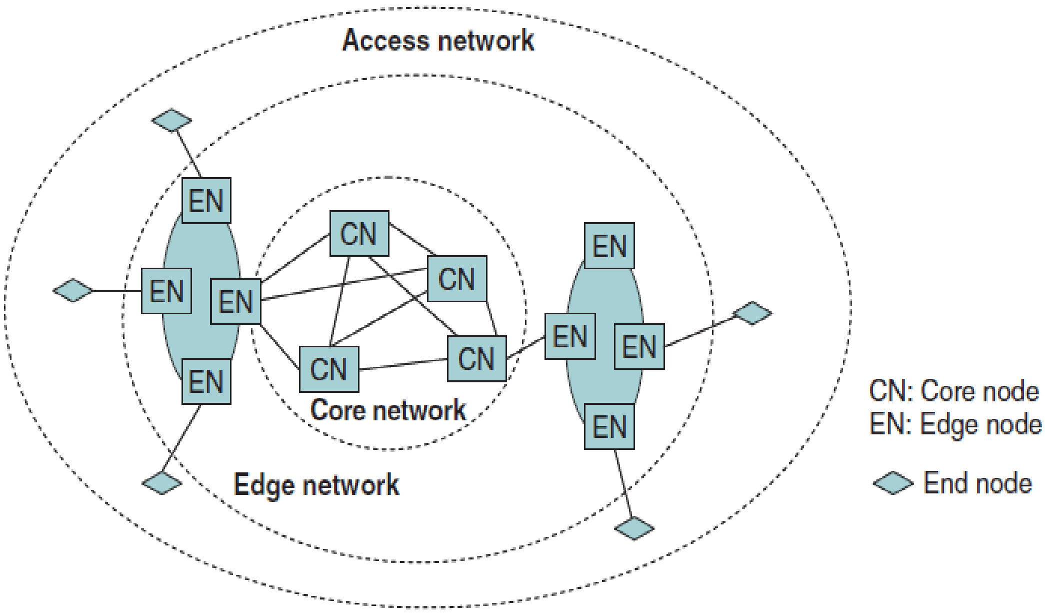

Fig 4.1 A typical optical networking architecture

4.2 Simulation for Q-factor

First segment of this chapter examines the performance of shortest path algorithm with a broad simulation. Here, we calculated the ideal light path connection for each connection request made by user. Basically, we found out shortest path and all possible paths for a particular source and destination. Using this algorithm, we have calculated the fiber dispersion time, total rise time, optical bandwidth, Q-Factor associated with all possible light paths for a connection request with specified edge nodes and finally BER for the shortest path. The Q-Factor is nothing but a marginal value in percentage, which characterizes the quality of the connections.

4.3 Network topology

The network model we used for simulation is given in the Fig. 4.1. The above mentioned network model consists of 10 nodes and 14 links. We have used a dynamic traffic model in our simulation, in which we have assumed that all the link requests have to be established instantaneously.

In our simulation work, we use few of the pre-defined parameters, which are mentioned in the next section this chapter.

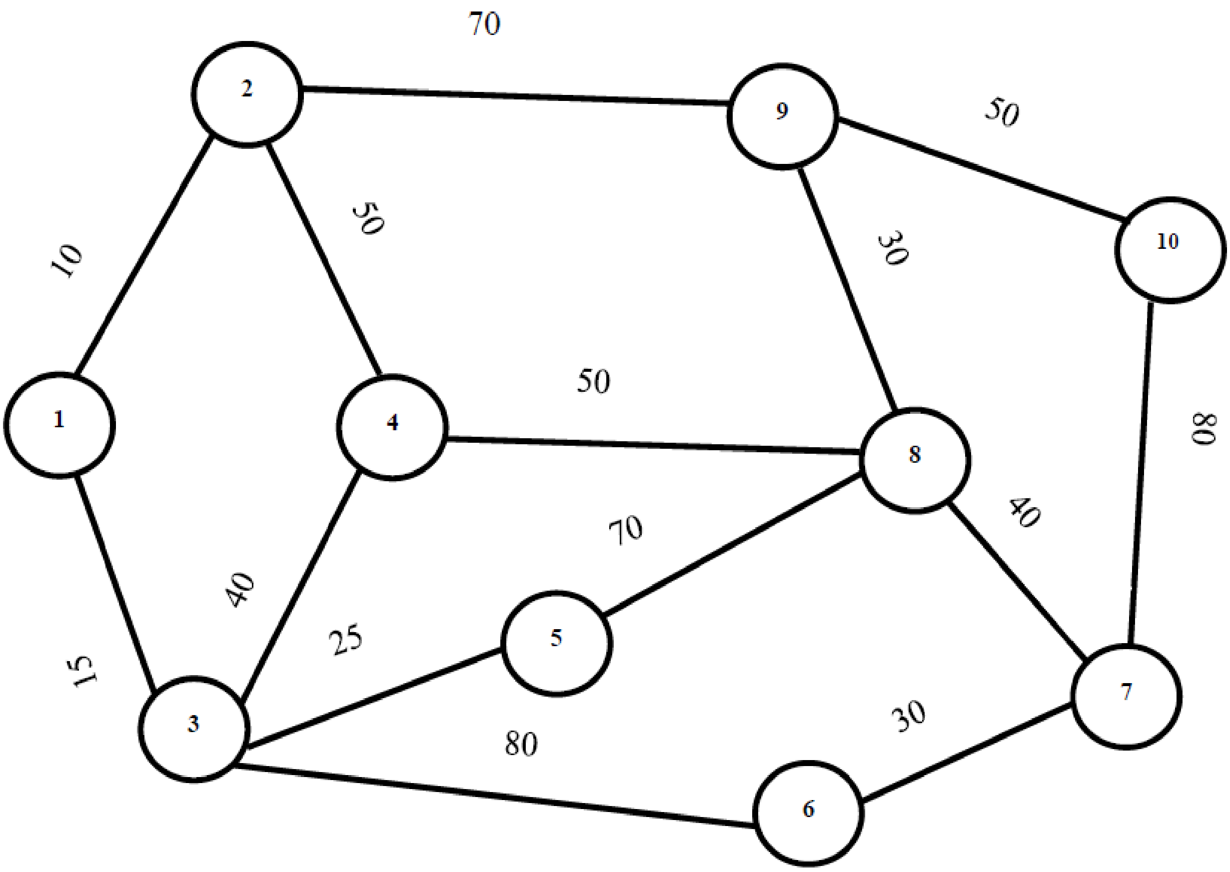

Fig. 4.2 Network Model (Note: All distance in km)

4.4 Simulation parameters

We have used an analytical model for finding Q-factor which is described by equations 3.1 and 3.2 as given in chapter 3.We have assumed some pre-determined values for certain parameters for performing simulation. These simulation parameters have been defined and explained in the table 4.1 [13].

Symbol	Name	Minimum value	Maximum value
p_{tx}	Average Transmitted Power	1 mW	5 mW
n_{sp}	Spontaneous Emission Factor of the Amplifiers	1	2
f_c	Carrier Frequency	191.5 THz	195.9 THz
G	Amplifier Gain	10 (10 dB)	1000(30 dB)
B_e	Electrical Bandwidth	5GHz	15GHz
B_o	Optical Bandwidth	10GHz	200GHz
N_{amp}	Number of Amplifiers	2	40

Table 4.1 simulation parameters

4.5 Simulation results and discussion

We assumed that the optical network under concern is a high speed WDM network. The analytical model for Q-Factor is used for determining quality of transmission. We took the following assumptions. The analytical model shown by equations (3.1) and (3.2) is described by a set of seven attributes (P_{tx},n_{sp}, fc, G, B_e, B_o, n_{amp}) as given in table 4.1.

We have considered the source destination pair (1, 9) in the given topology. All possible paths and shortest path between the source and destination is calculated using the shortest path algorithm. Q-Factor plots for all links in a particular selected path of source destination pair (1, 9) is given in the Fig. 4.3 and Fig. 4.4.Here, we have taken transmitted power from 0.1 mW to 3 mW.

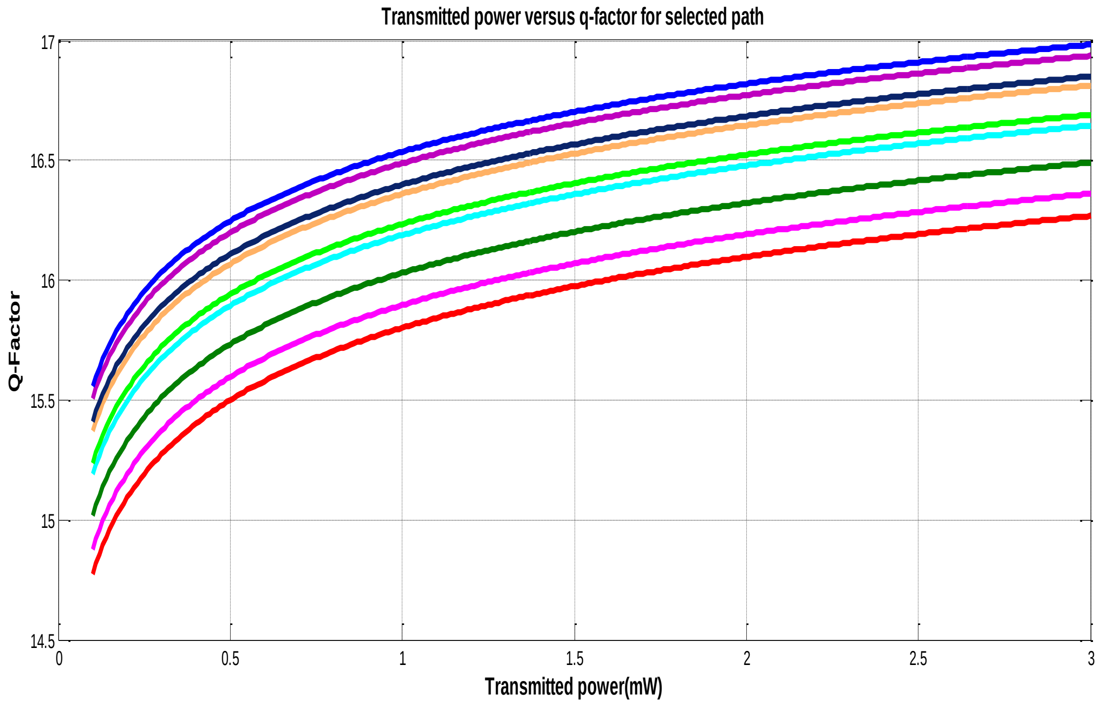

Fig. 4.3 Q-Factor plots for all links in a selected path (1) of source destination pair (1, 9)

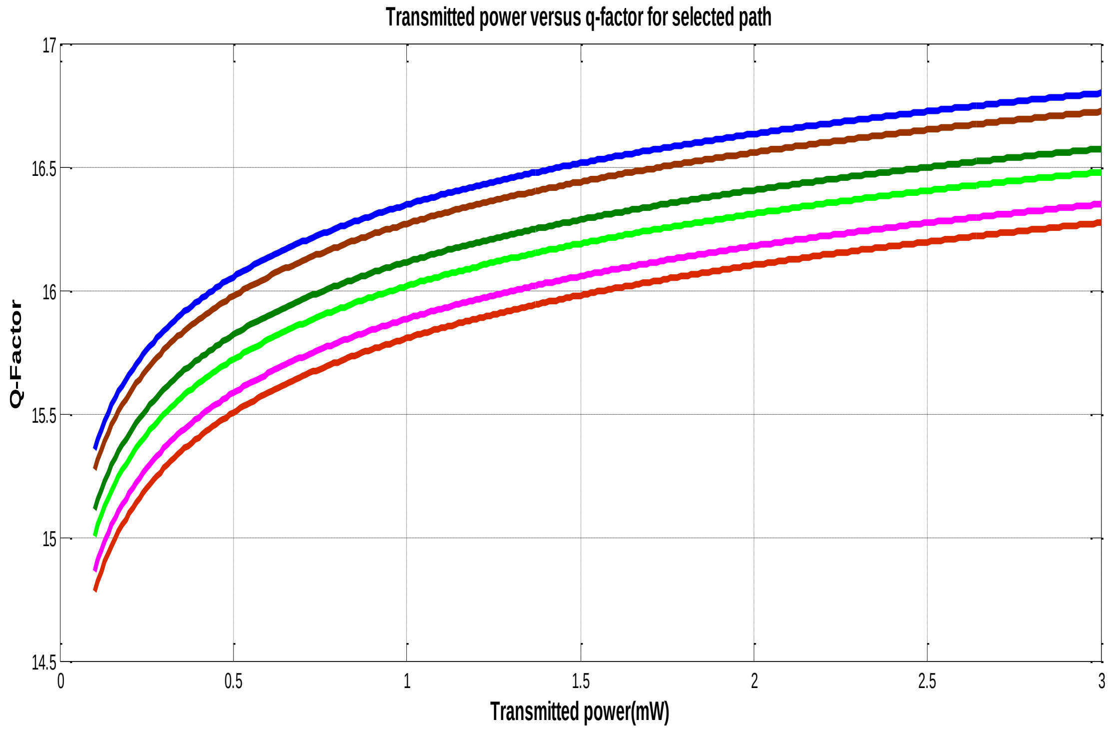

Fig. 4.4 Q-Factor plots for all links in a selected path (2) of source destination pair (1, 9)

Any point to point link taken is assumed to be equipped with cascaded optical amplifiers. Values of seven attributes determining Q-Factor has been selected within a range as given in the Table 4.1.Time response of the system has been calculated from different rise times like transmitter, receiver, photodiode and from fiber dispersion time.

The total fiber dispersion time is calculated from the algorithm. From that, total rise time or system rise time is calculated using the equation (3.6). Relationship between electrical bandwidth, optical bandwidth is given by equation (3.4).Moreover, system rise time and bandwidth of the optical communication system is related by the equation (3.5).

Thus from the system rise time optical bandwidth and electrical bandwidth is calculated and OSNR and thus Q-Factor is obtained.

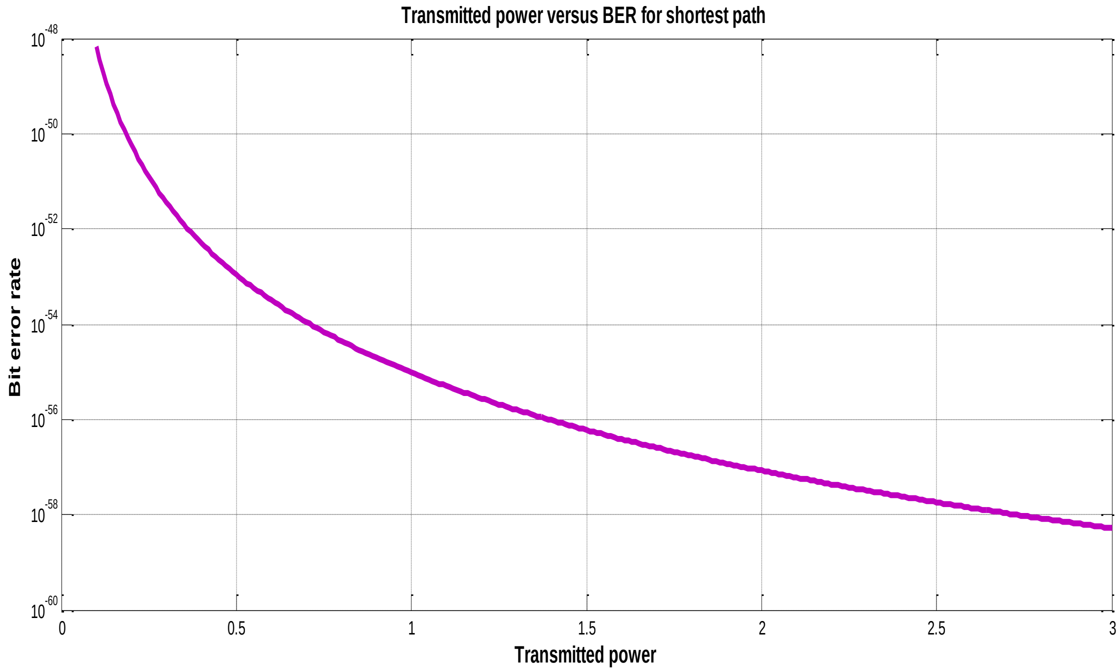

Fig. 4.5 Bit error rate versus transmitted power (mW) of source destination pair (1, 9)

After finding the Q-factor, we have calculated BER from it using the relationship as given in the equation (3.3).From the relationship between them, higher value of Q-Factor results in a lower value for BER [7].Thus any basic transmission system should have a decent value of Q-factor so that BER can be reduced to a minimum value. Here, we have calculated BER for the shortest path available for source destination pair (1, 9).

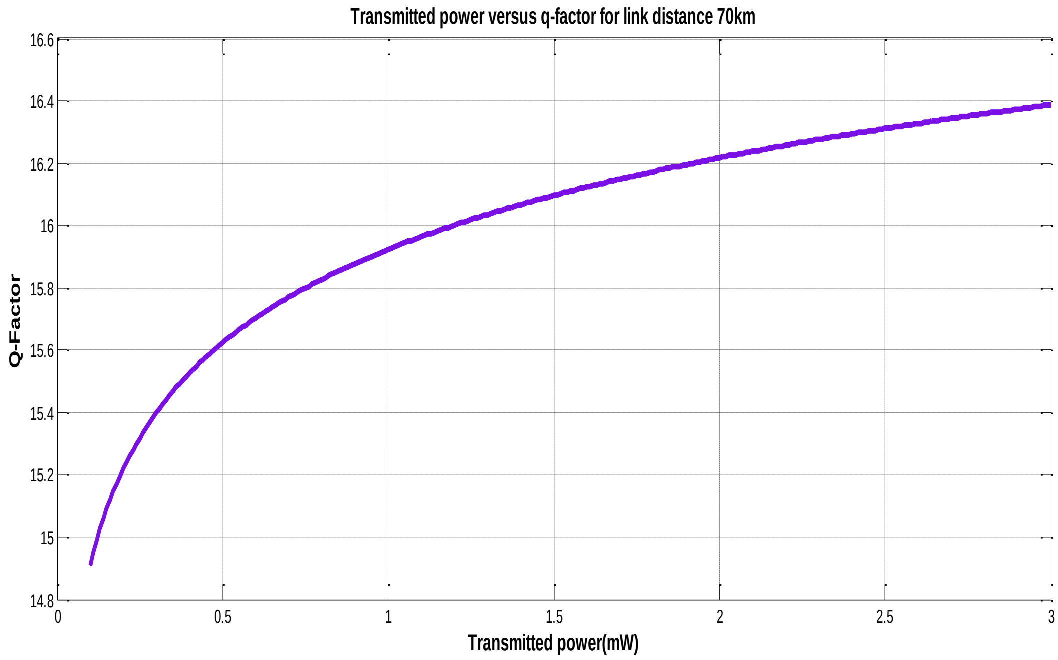

Fig. 4.6 Q-factor versus transmitted power (mW) for link L1 of shortest path from 1-9

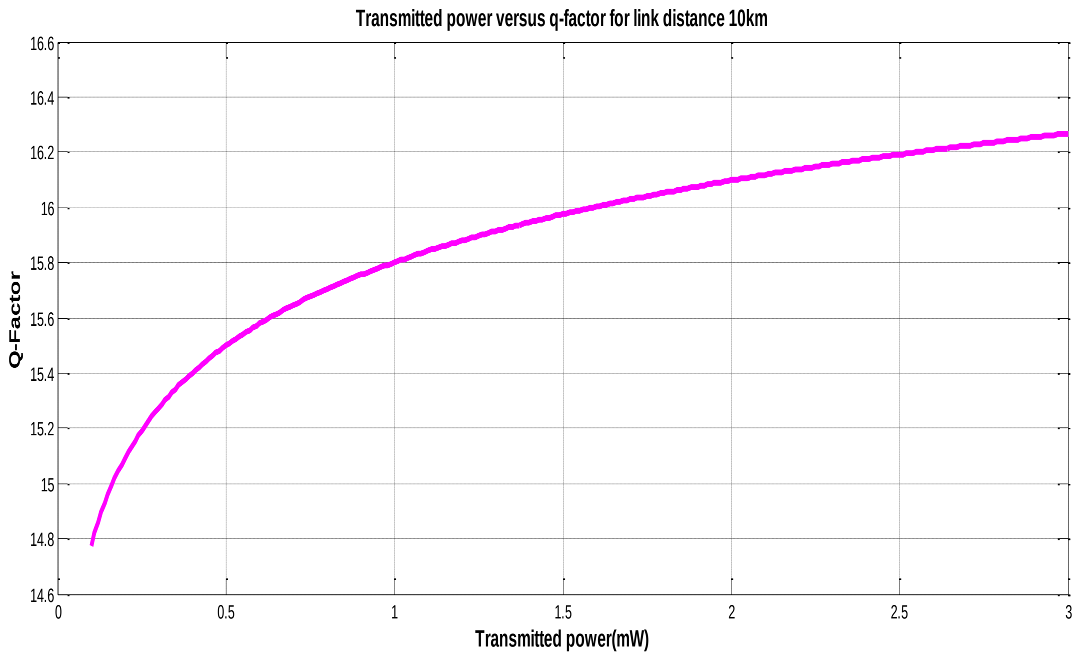

Fig. 4.7 Q-factor versus transmitted power (mW) for link L2 of shortest path from 1-9

Fig 4.6 and Fig 4.7 shows the plot of Q-factor for individual links of the shortest path for the given source destination pair (1, 9).Here link distance for the two links L1 connecting 1-2 and L2 connecting 2-9 as per topology is 10 km and 70 km respectively.

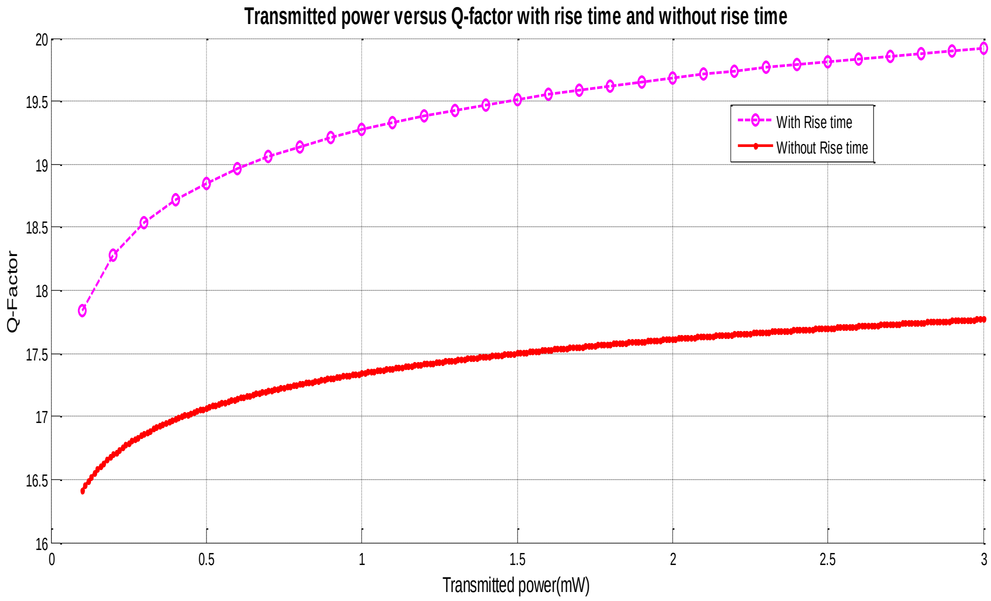

Fig. 4.8 Q-factor versus transmitted power with rise time and without rise time

Q-factor against transmitted power with rise time and without rise time is given in fig 4.7. Here, rise time means we are referring to system rise time or total rise time which is a combination of various component rise times as mentioned in section 3.3. The effect of system rise time on Q-factor indicates how transmitter and receiver properties affect the quality of transmission in optical communication. We need to choose the transmitter and receiver rise times and other rise times to such a minimum value so that we can get the best and optimization in fiber optic channel design.

path number(path index)	% Q-factor
1	85
2	82.8
3	83.1
4	82.5
5	82.5
6	83.2
7	83.8
8	83.5
9	84
10	83.9
11	83.9
12	83.9
13	83.9
14	84.3
15	84.2
16	84.5
17	84.7

Table 4.2 percentage of Q-factor for all possible paths of source destination pair (1, 9)

Percentage of Q-factor for all possible paths including shortest path is given in the table 4.2.Here, we have taken source destination pair (1, 9) as mentioned earlier in this chapter. According to the given topology, shortest path algorithm calculates 17 paths totally in which one of them is the shortest possible path from source to destination. As per the table 4.2, first path indicates the shortest possible path of source destination pair (1, 9).We can see that percentage of Q-factor is maximum for the shortest path and minimum for path 4 and 5.

The Fig. 4.8 shows a histogram representation of above mentioned details.

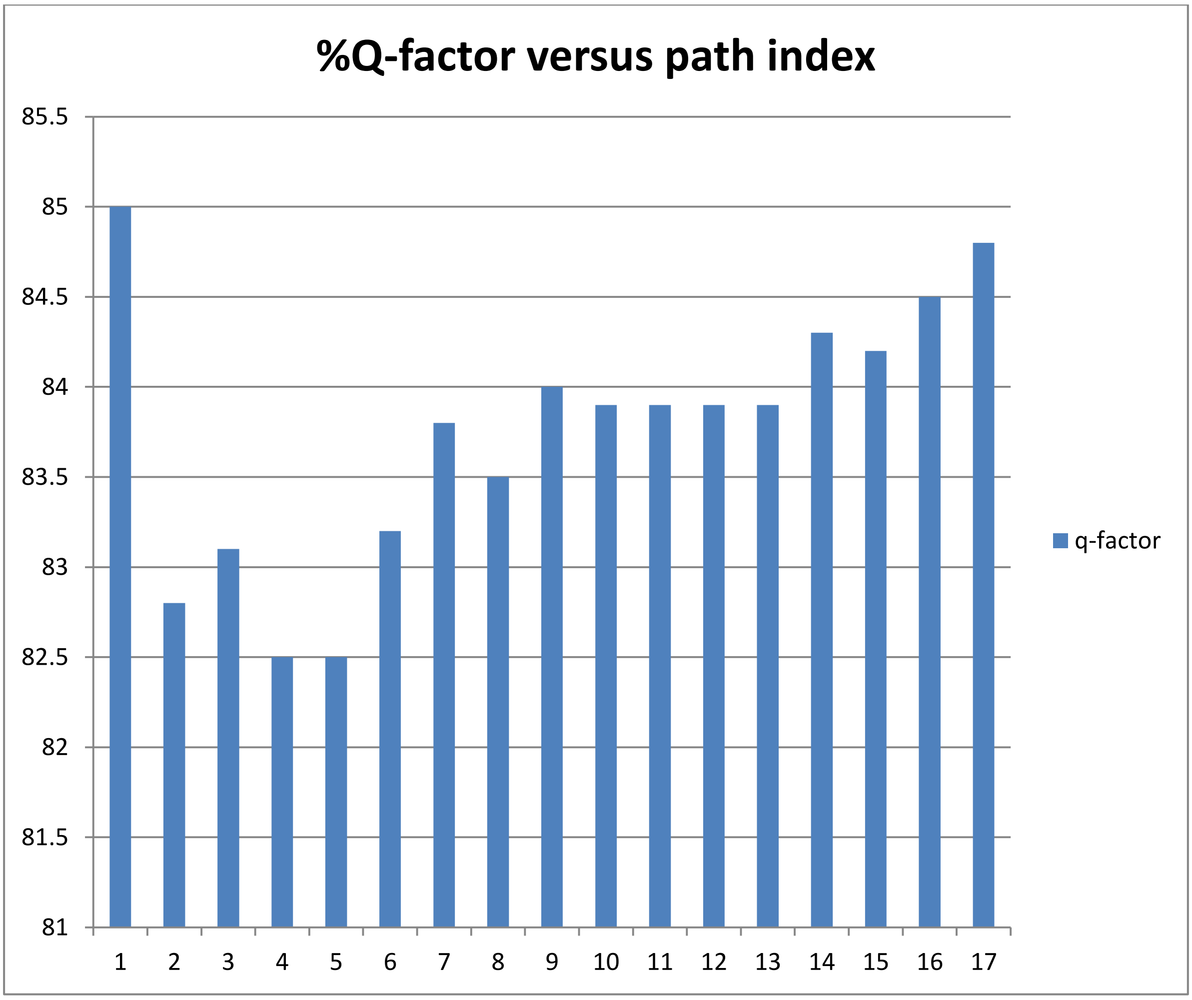

Fig. 4.9 Histogram representation of percentage of Q-factor for all possible paths of (1, 9)

Chapter 5

Conclusion and future work

We have calculated Q-factor, BER for the given topology using the analytical model for Q-factor and considering the effect of rise time. The shortest path algorithm is used for calculating shortest possible path and all possible paths for the source destination pair. We have chosen source destination pair as (1, 9) for our simulation work.

In chapter 2, optical communication system is explained along with various components constituting the system. Chapter 3 mainly includes the definition of quality of transmission and brief explanation of rise time along with equations supporting the relationship of rise time with parameters like optical bandwidth, electrical bandwidth etc. Chapter 4 includes the network topology used for simulation and also the results obtained.

Here by transmission data rate, we are indirectly referring to the optical bandwidth of the system. With increase in the length of the cable, the magnitude of the dispersion problem increases and hence the transmission data rate decreases with fiber length. We need more transmitted power to get the same BER in the system, if the fiber length increases. Also, if the power is held constant, the BER increases as data rate increases. So in order to get the lower BER and good performance in communication system, the overall rise time must decrease on the higher data rate. The effect of system rise time on Q-factor indicates how transmitter and receiver properties affect the quality of transmission in optical communication. We need to choose the transmitter and receiver rise times and other rise times to such a minimum value so that we can get the best and optimization in fiber optic channel design. Except the fiber dispersion which is expressed in picosecond, rest of the rise times is usually expressed in nanosecond.

Our research work can be extended for different topologies and can be implemented for multiple optical networks by taking care of some new parameters.

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