CROSSTALK AWARE LIGHT-PATH SELECTION IN OPTICAL WDM/DWDM NETWORKS

by

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2012

Dedicated

to

my parents

National Institute Of Technology
Rourkela

CERTIFICATE

This is to certify that the thesis entitled, "**CROSSTAL AWARE LIGHT-PATH SELECTION IN WDM/DWDM NETWORKS**" submitted by TUSAR RANJAN SWAIN in partial fulfilment of the requirements for the award of Master of Technology degree in **Electronics and Communication Engineering** with specialization in "**Communication & Signal Processing**" during session 2011-2012 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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Abstract

Physical layer impairments are the major limitation for the high speed optical WDM/DWDM networks. They significantly affect the signal quality resulting poor quality of transmission which is normally expressed in terms of bit-error rate. To cope of with the future demand, increase in the no of channels and data speed further enhances these impairments. Hence new techniques are needed, which mitigate these impairments and ensure a better quality of transmission. Among the physical layer impairments we have studied the impact of in-band crosstalk on transmission performance of a transparent WDM/DWDM network. Error probabilities and power penalties produced by crosstalk are also investigated. As traditional RWA scheme pays a little regard to the physical layer impairments and cannot provide optimized network performance in practical networks, we have proposed a novel BER constrained, FWM aware RWA algorithm. The performance of the proposed algorithm is demonstrated through simulation and the results show that our algorithm not only gives a guaranteed quality of transmission but also improves the network performance in terms of blocking probability.

Keyword- Bit error rate, In-band crosstalk, routing and wavelength assignment (RWA), OADM/OXC, power penalty (pp), WDM/DWDM.

List of Abbreviations

IP	Internet Protocol
LPs	Light paths
BER	Bit Error Rate
WDM	Wavelength Division Multiplexing
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
ASE	Amplifier Spontaneous Noise
PMD	Polarization Mode Dispersion
FWM	Four Wave Mixing
OXC	Optical Crossconnect
OADM	Optical add/drop Multiplexer
OEO	Optical-to-Electrical-to-Optical
QoT	Quality of Transmission
QoS	Quality of service
RWA	Routing and Wavelength Assignment
GMPLS	Generalized Multiprotocol Label Switching
OOK	On-off Keying
OLTs	Optical Line Terminals
ITU	International Telecommunication Union
SONET	Synchronous Optical Network
XPM	Cross Phase Modulation
SRS	Stimulated Raman Scattering

List of Symbols

λ Wavelength

ε_k Crosstalk component

f Frequency

$\sum$ Summation

$\prod$ Multiplication

σ Variance

L length

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Chapter -1

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1.1 Introduction

Optical WDM/DWDM networks are no doubt, the backbone modern communication because of their high throughputs of the order of terabits per second. They have the capacity to satisfy emerging application such as video services, medical imaging and distributed CPU interconnects [1]. During the past couple of years, optical networking has undergone tremendous changes and the trend clearly shows an evolution path towards lower cost and high capacity networks (i.e. more wavelength and higher data rate) [2].

The first generation of optical networks provides point-to-point transmission service and in these networks all routing and switching actions are done in electronic domain. It means optical-electrical-optical (OEO) conversion is employed at every node to regenerate and retransmit the data signal. For such opaque transmission the expenses are quite high [3], mainly due to the large number of regenerators required at each node for a large-scale network. An OEO node, especially based on electronics, will have its own scalability issues related to cost, space requirements, power consumption and heat dissipation [1, 2]. In order to make a cost effective network, development in DWDM techniques and DWDM component technology (e.g. amplifiers, lasers, optical switches, optical add/drop multiplexer) leads us towards all-optical or transparent network.

In a transparent optical network, the routing is done without requiring any intermediate OEO conversion and buffering at each node (i.e. everything is done in the optical domain). This eliminates the electronic bottleneck in the current networks. In a large number of literatures it has been shown that the economy and scalability of the network are greatly enhanced through the use of transparent networking layer [4]. In our work, we entirely focused on such transparent network, where a connection has to be established between a source and destination via an all-optical WDM channel, called light path.

While setting up a light path using various routing and wavelength assignment techniques (RWA), we assume that our optical medium is an ideal one which carries our information signal without any bit error. But in reality, the transmission impairments, which occurs due to non-linear nature of the fibre and the non-ideal nature fibre components (OXC, OADM), may significantly affect the quality of the light path. Sometimes the signal degradation is so high that the received bit-error rate (BER) becomes unacceptably high and the light path would not be able to provide good quality of service to the connection request. Such light path, with poor signal quality, should not be used for connection set-up by the network layer. Hence we have to consider the impact of impairments during routing and wavelength assignment.

1.2 Literature survey & Motivation

During past few years, there has been extensive research regarding the optical transparency and the physical layer impairments. Transparency leads us towards more economic and scalable networks, but simultaneously it losses the benefit of signal regeneration at the intermediate node [3]. While setting up a connection between a source and destination for a transparent network the data signal remain in optical domain for the entire light path. Noise and signal distortion due to physical layer impairments accumulates as the signal travels through the light path and causes significant signal degradation. At the destination node the accumulated noise became so high that the BER become unacceptably high, and the light path is not usable.

The routing and wavelength assignment task in optical network is done by the network layer. While making all these decisions the network layer assumes that my physical layer is ideal. But in reality the physical layer is not an ideal one, and has a lot of impairments associated with it. Hence there is a number of PLI-aware RWA algorithms are given in literature [3, 5, 6, 7] in which the impairments are taken into consideration while routing by the network layer. Most of them consider linear impairments because their effects on end to end light path might be estimated from link parameters, and hence could be handled as a constraint on routing [1,3]. There are very few articles, where authors have taken non-linear impairments into consideration because they are more complex and it is difficult to consider both linear and non-linear PLIs and their dependencies while taking routing decisions [8, 9]. Analytical model for some impairments due to non-linearity are still unavailable.

A general approach for physical layer impairments aware based RWA algorithm [1] is given in figure 1.1. Here the RWA block is responsible for routing and wavelength assignment and these two functions are done either in two stages or in a single stage (integrated). In the quality test block, the QoT of transmission is considered by taking different PLIs into consideration. These PLIs may be obtained either by using the analytical model or by the manipulation of some real-time quality metrics (e.g. OSNR, BER, Q-factor, etc.). If the estimated OSNR/BER/Q-factor satisfies the threshold requirement, then the connection will be established on that light path. Otherwise, RWA algorithm may select an alternate route and/or wavelength and repeat the same procedure.

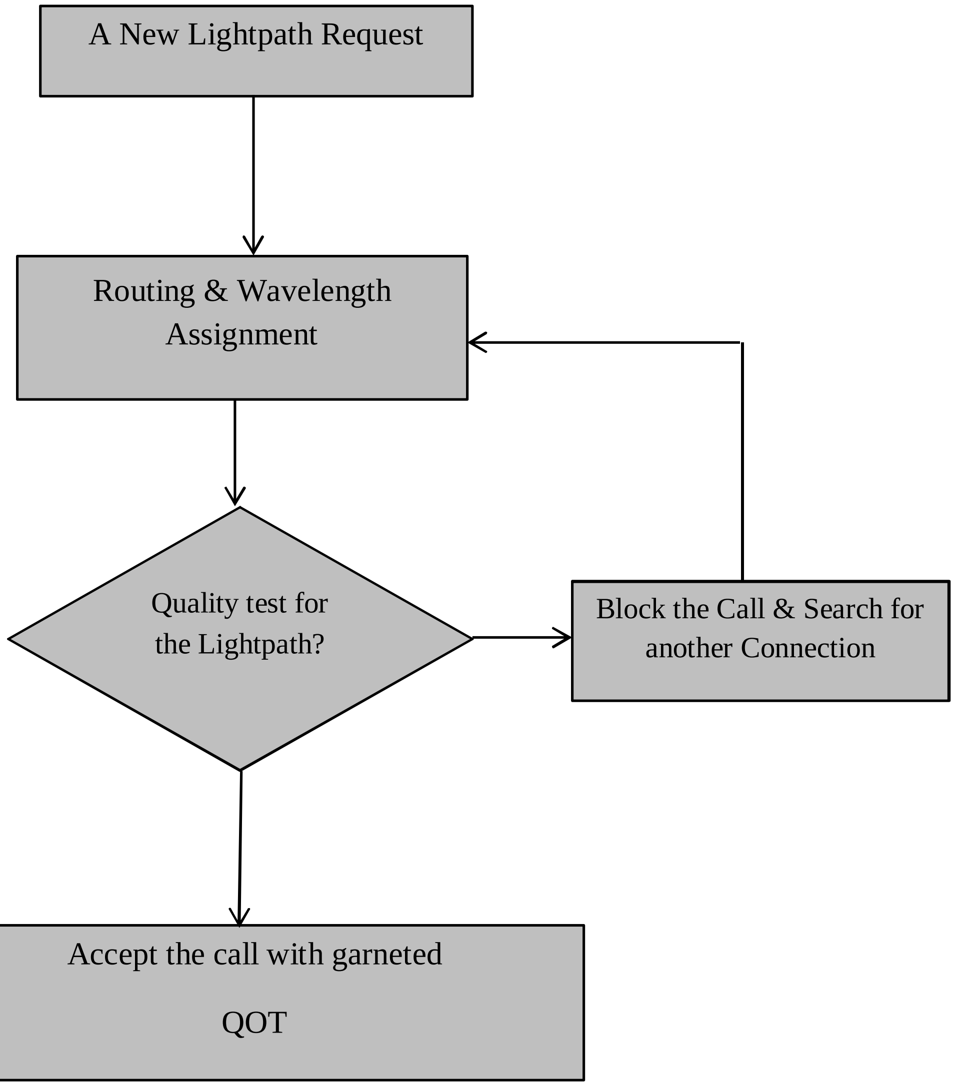

Fig 1.1 A general flowchart for impairments aware RWA algorithms

In the last few years, a lot of research articles [5, 8, 9, 10] has been come up with a number of impairment constrained based routing algorithm, where authors has taken different PLIs into their consideration. In 1999, Ramamurthy et al. [10] proposed the first PLI constrained based RWA algorithm taking amplifier spontaneous noise (ASE) into consideration. They evaluated BER as the QOT parameter and allow the light path that satisfies the threshold (in terms of BER) requirements. Similarly Huang et al., considered ASE and polarisation mode dispersion as PLIs and express the quality of transmission in terms of OSNR. Table 1.1 shows some of the articles that we have followed with the impairments that are taken into their consideration.

Table 1.1

Authors	PLIs taken into consideration	QoT Parameter
Ramamurthy et al. [10]	ASE	BER
I Tomkos et al. [8]	ASE,FWM,XPM	Q-factor
Huang et al. [3]	ASE,PMD	OSNR
C.Politi et al. [9]	FWM,XPM,OSNR	Q-factor
Deng et al. [11]	ASE, In-band Crosstalk	Q-factor & BER
N. Sengezer et al.[6]	ASE, Crosstalk, PMD	Q-factor

1.3 Proposed Work

The main objective of our work is to investigate the impact of the transmission impairments and to design an algorithm, which takes these impairments in to their consideration, so that the QoT is guaranteed. We express the QoT in terms of BER. Instead of considering all the impairments, we mainly focused on component crosstalk and four wave mixing, which are the significant impairments in high-speed networks (10Gbps). Component crosstalk arises due to non-ideal nature of the optical components like OXC/OADM and the noise due to crosstalk accumulate as the signal travel through the light path. FWM arises to fibre non-linearity. In our work we also discuss different mathematical modelling of these impairments and followed a simplified model based on Taylor series expansion.

1.4 Objective of the Thesis

The objective of the thesis is as follows

- To investigate different type of physical layer impairments in WDM/DWDM networks.
- Highlight the in-band crosstalk and FWM (Major PLIs).
- To analyse the mathematical models for in-band crosstalk.

- To provide a novel algorithm that takes these impairments during routing and wavelength assignment.
- To improve the network performance.
- To guarantee quality of transmission (QoT) in terms of BER

1.5 Organization of the Thesis

Rest of the thesis is organized as follows

- Chapter 2 give a basic introduction to WDM/DWDM networks and the components used in these networks. We also discuss different linear and nonlinear physical layer impairments in this chapter.
- Chapter 3 discuss about in-band crosstalk, FWM, and their mathematical models. Here we have also shown their impacts on networks performance by simulations.
- Chapter 4 discuses about the BERC constrained algorithm and the simulation results for selected data path.
- Finally in chapter 5 we conclude our result with, future scope related to this work.

Chapter-2

WDM/DWDM Networks

Optical WDM Networks

Optical Components

Physical Layer Impairments

Crosstalk

2.1 Introduction

Optics is clearly the preferred means of transmission, and WDM transmission is now widely used in the networks. In recent years people have realized that optical networks are capable of providing more function than just point-to-point communication. Bandwidth that an optical network support is in the terabit range, and for this high data rate, it became more difficult for the electronics to process the data. In first generation networks the electronics at a node not only handle the data intended for that node but also all the data that has to be passed through that node for some other node. Hence burden on the underlying electronics increases. That means we need faster electronic switching circuit, which can operate in the terabit range. But electronic circuits have some limitation and till date their maximum speed is in the Gigabit range. In order to utilize the enormous bandwidth of optical fibre and to reduce the opto-electronic miss-match we move towards WDM networks. Among the WDM networks, opaque network are used in early stages and they consume more power. Another problem with these networks is that they are not scalable to satisfy future demands. To overcome these drawbacks people go for all optical/transparent networks, which are more scalable, consumes less power and has higher data carrying capacity.

2.2 Architecture of a WDM Network

WDM networks are second generation optical networks where data are routed through nodes in the optical domain reducing the burden on the underlying electronics. The basic architecture [12] of such a network is given in the figure 2.1. This network supports a variety of client types such as IP routers, ATM switches, SONET/SDH terminals and ADMs. They provides light path to these users. A light path is a dedicated optical connection between source and destination with a particular wavelength through the entire path (wavelength continuity constrain).

In figure 2.1 we have shown four connections. The lightpath between C-B and E-F does not share any common link, so they can use the same wavelength. At the same time the light path between E-F and E-B share a common link and hence they must have to use different wavelengths. See that every light path satisfies wavelength continuity constrain as we have assumed that all the nodes does not have wavelength conversion capability.

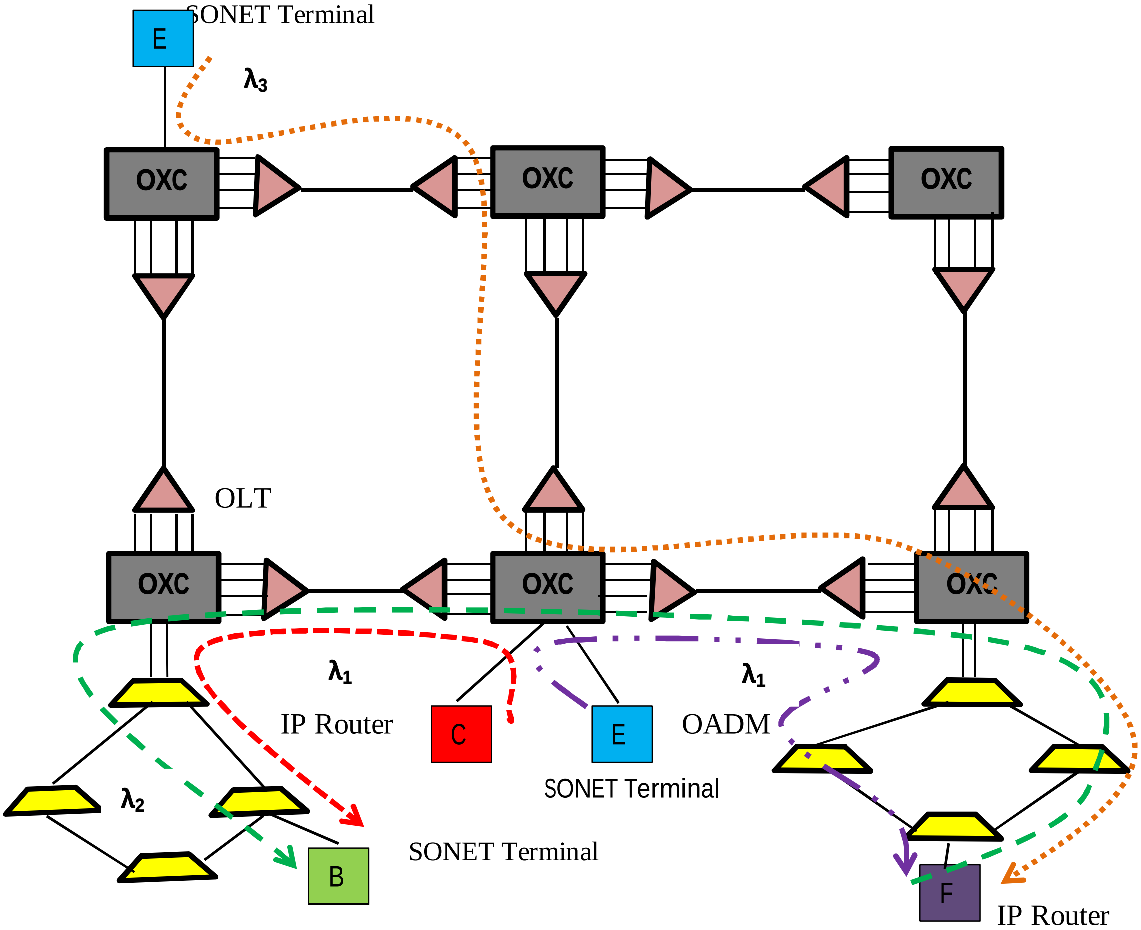

Fig.2.1 A WDM Wavelength Routed Network

2.3 Optical Layers

Optical networks are very complex in structure and different functions have to be performed by different components present in the networks. One of the problems in these networks is the internetworking of the components, which are taken from different venders. In order to bring all components into a common platform layer architecture is generally followed. Each layer performs some function and provides services to the next higher layer.

Normally the objective of a network is to provide connections between the users. Different control mechanisms and protocols are followed by separate layers in the layer architecture to set up or taking down a connection. It is important to define the function of each layer and the interface between the layers, because it allows the vendors to manufacture a variety of products performing some functions of some layers and provides the appropriate interfaces to communicate with other products of other vendors, performing the functions of other layers. Fig. 2.2 shows different layers in a network that was followed throughout the world as a common standard.

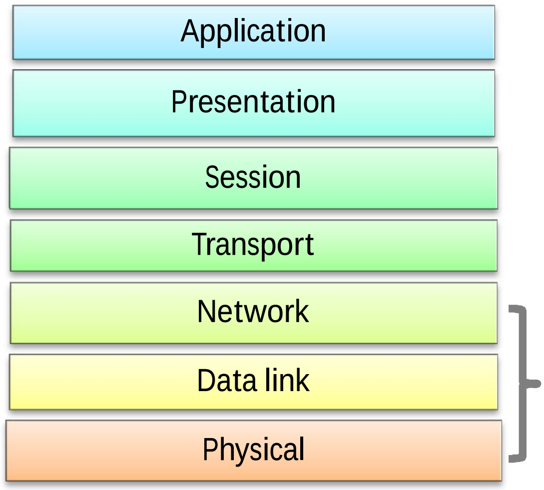

Fig 2.2 Classical OSI layer hierarchy

Physical layer provides a link with a certain amount of bandwidth to the upper layer. It may be optical, wireless or twisted pair cable. The data link layer is responsible for multiplexing and de-multiplexing of data that are sent over the physical layer. Framing of data's are also done by this layer. Network layer provides virtual circuit to the higher layer. A virtual circuit means an end to end connection with a set of quality of transmission parameters associated with it [12]. It performs the routing and wavelength assignment function of taking a data from its source and delivering to its destination.

While making the entire routing decision network layer assumes that my physical layer is ideal, i.e. it does not have any impairment. But in reality physical layer has a lot of impairments which significantly affect the signal quality during transmission from a source to destination. Hence in order guarantee a QoT on the light path, some shorts of cross layer optimization methods are followed, where the network layer takes these impairments (from physical layer) in to their consideration.

Huang and et al. proposed a module architecture, which is given in fig. 2.3. Here the physical layer module model the impairments effects and keep the track of them. The QoT is measured analytically at the destination and this information is provided as a feedback to the network layer module [3]. Network layer after getting the information take the decision for an optimal light path for which signal quality is guaranteed.

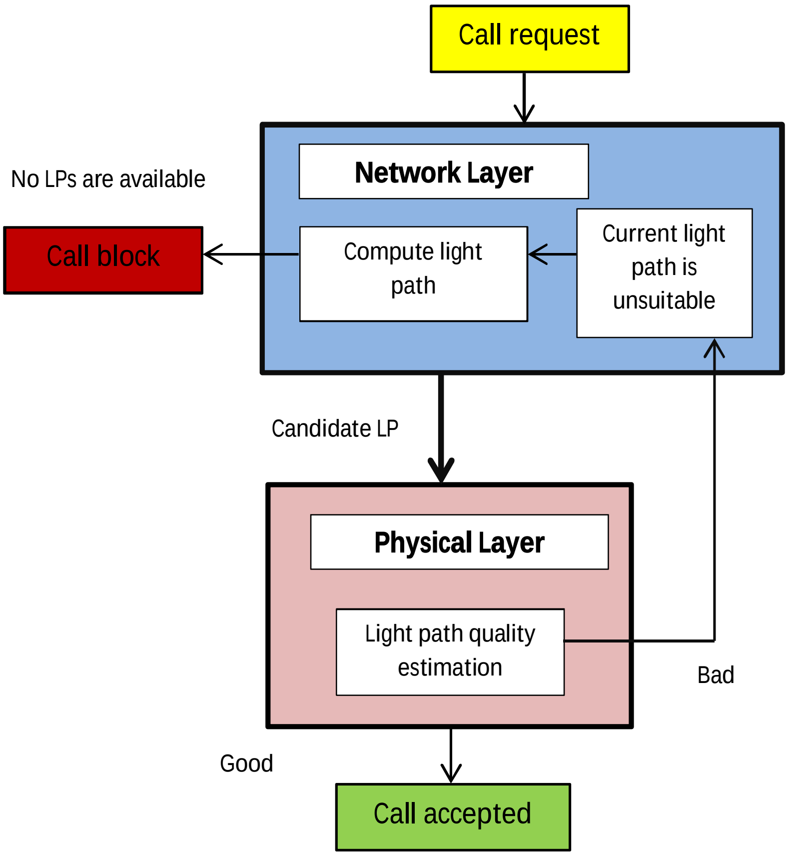

Fig. 2.3 An overview of crosslayer architecture used in impairment aware RWA.

2.4 Optical Components

In the introduction we have already discussed the motivations for deploying WDM networks. These circuits are capable of providing circuit switched end to end fibre channel called lightpaths. These growths (in terms of high data rate) in optical networking are possible only due to development of optical components that are used at every routing node. All the routing is done by these components and the signal remain in optical domain throughout the path.

The basic architecture of a WDM network is shown in fig.2.1 and it consists of several components like optical line terminals (OLTs), Optical add/drop multiplexer (OADM) and optical crossconnects (OXCs). These components are connected by optical fibre. In addition to these components we also have optical line amplifier (EDFA) along the fibre line at periodic locations to amplify the light signal. Sometimes OLTs, OADM and OXCs may themselves incorporate optical amplifier to make for the losses. The function of OLTs is to multiplex and demultiplex several wavelengths into a single fibre and they are normally used at either end of a point-to-point link. OADMs are used in some location where, a few no of wavelength need to be terminated locally and others need to be routed to other destinations. OXCs performs the same operation but in a large scale in terms of numbers of ports and wavelength involved. These components are used in linear, ring and mesh topologies or in order to interconnect multiple rings. Users or clients of the network are connected to the OLTs, OADMs and OXCs. In the next section we discuss the detail architecture of these components.

2.4.1 Optical Line Terminals (OLTs):

They are the simple network component from architectural point of view. Generally they are used to multiplex and de-multiplex wavelengths at either end of a point to point link. Fig 2.2 shows the internal structure of an OLT. It consist of three functional elements [12]

- Transponders
- Wavelength multiplexer
- Optical Amplifier

Transponders are used to convert the signals from a client into a signal suitable for use inside the optical network. Similarly in the reverse direction it adapts the signal from optical network into a signal suitable for clients. Adaptation includes several functions such as, conversion into a wavelength in the 1550 *nm* range (zero dispersion) set by international Telecommunication Unions, addition of forward error correcting code or some other overhead for the purpose of network management.

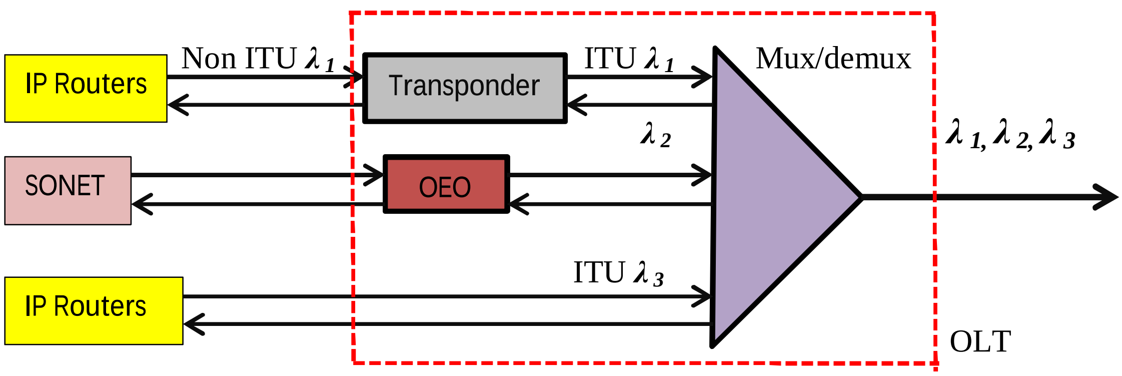

Fig. 2.4 Block diagram of an Optical Line Terminal

2.4.2 Optical ADD/DROP Multiplexer:

OADM provides a cost effective means for handling the entire traffic in an optical networks. They are used at amplifier site in long haul networks and as a stand-alone network element in the metro networks. Several architectures has been given for building an OADM but normally in most practical networks OADMS based on fiber Bragg grating are used. In the architecture shown in the fig. 2.4 all the incoming signals get demultiplexed and some of these channels may be dropped locally and others get passed through.

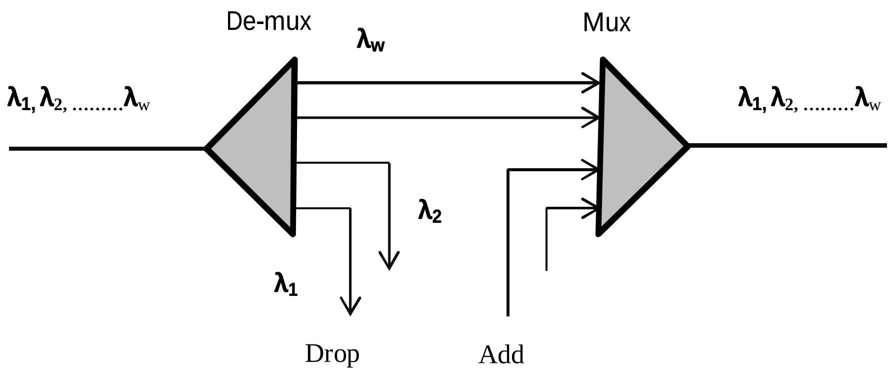

Fig. 2.5 Internal architecture of an optical ADD/DROP multiplexer.

2.4.2 Optical Cross Switches:

OADMs are useful only when our network topology is simple in structure like linear and ring networks. But as the complexity increases in terms of larger no of wavelength and development of mesh topology, additional network elements are needed. This element is the optical cross connects (OXC).

Suppose consider a large office in city where several fiber links terminates, each carrying a large number of wavelengths. A number of these wavelengths might not be terminated at the same office, but rather transmitted to the next office. These functions are done by OXCs.

An OXCs provides several key function in a large network such as

- Service provisioning
- Wavelength conversion
- Multiplexing
- Protection

- Bit rate transparency
- Performance monitoring

An OXC can be functionally divided into a switch core and a port complex [12]. The port complex is used for interfacing with other equipment and may or may not have OEO converters. The switch core performs the all crossconnect function. The basic architecture of an OXC is given in the fig. 2.56.

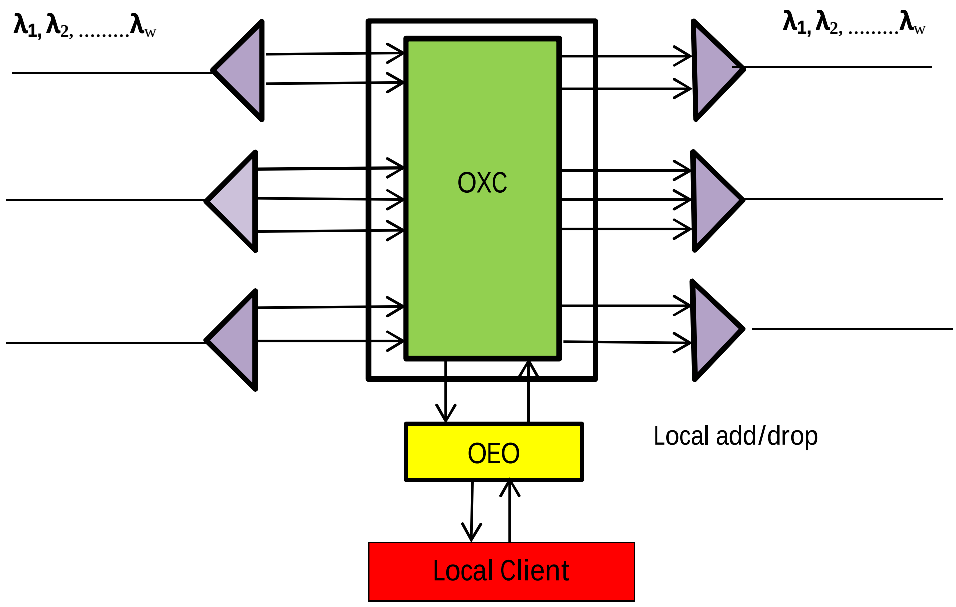

Fig. 2.6 Architecture of an OXC module.

2.5 Overview of Physical Layer Impairments:

Impairments in WDM networks have been classified into two categories: linear and non-linear impairments [1, 2, 12] . This classification is based on the dependence on intensity of light or not. Linear impairments are static in nature and non-linear are dynamic in nature. Linear impairments are independent of signal power and affect each wavelength individually. Whereas non-linear impairments depend on signal power and it not only affect the individual channel but also causes disturbance in between the channels. So in an optical network allocation of new lightpath affect the existing lightpath. Fig 2.3 shows different impairments in optical networks and in the very next section we will discuss all of them one-by-one.

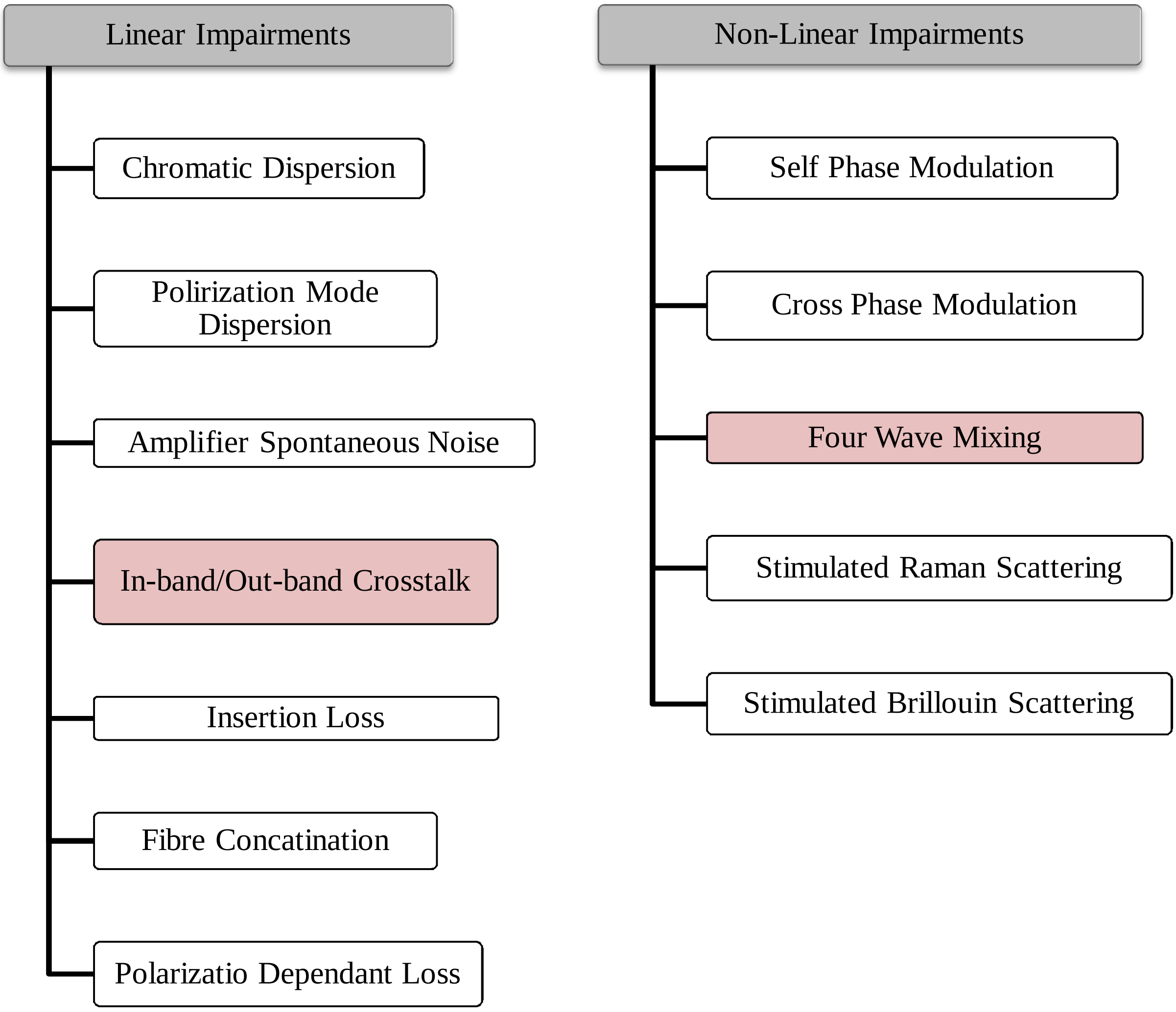

Fig. 2.7 Classification of physical layer impairments

2.5.1 Linear Impairments

A) Power Loss

It is the loss in power that occurs as the signal travels along the fibre and may be either intrinsic fibre loss or extrinsic bending loss. Intrinsic loses are due to refection, refraction, attenuation, absorption, Rayleigh scattering or by optical component insertion loss [1]. Extrinsic losses occur in fibre due to micro and macro bending losses. Insertion losses introduced by optical components such as couplers, filters, switches and multiplexer/de-multiplexers are independent of wavelength.

$$p_{out} = p_{in}.e^{-\alpha l} \quad (2.1)$$

Where α is the fibre attenuation constant.

B) Chromatic Dispersion

Dispersion arises when different components of a transmitted signal travels at different velocities in the fibre and reach the receiver at different time. Chromatic dispersion is the term given to the phenomenon by which different spectral components of a pulse travels at different velocities. Chromatic dispersion causes optical pulse broadening which, results inter symbol interferences. In high speed networks it causes a serious problem. When the signal travels though several fibre links, the total dispersion is the sum of the dispersion causes by the individual links. To reduce chromatic dispersion, dispersion compensated fibres (DCF) are used and they are suitable for long-haul as well as metro networks. A fibre of length L_f and dispersion D_f can be compensated by using a spool of DCF of length L_c and dispersion parameter D_c such that

$$D_c L_c + D_f L_F = 0 \qquad (2.2)$$

There may be some wavelength which may get over-compensated and some get under-compensated due to imperfect matching between the dispersion slopes of CD and DCF.

C) Polarization Mode Dispersion

Fibre installed in the network may contain impurities or may be subjected to envourmental stress such as local movement and heating. The impurities and irregularities result different polarization of the optical signal that causes different group velocities, so that pulse spreads in the frequency domain known as PMD. The differential group delay is given by

$$\Delta\tau = D_{pmd} \times \sqrt{L} \quad ps \qquad (2.3)$$

Here D_{pmd} is the PMD parameter of the fibre. Because of the square-root relationship with the fibre length the pulse broadening is less in comparison to chromatic dispersion. PMD accumulate along a light path and at the end it is given by [1].

$$PMD_{lightpath} = \sqrt{\sum_{fibre\ links\ along\ the\ route} PMD(f)^2} \qquad (2.4)$$

It becomes a major limiting factor for WDM system designed for longer distance with a high data-speed. As the data-speed increases (above 40Gbps) higher order PMDs come into picture. This problem can be reduced by shortening the optical transmission distance by placing OEO converters in between the nodes. However it is not economically viable and we go for dispersion compensation modules at OADMs, OXCs or at amplifier sites.

E) Amplifier Spontaneous Noise

ASE noise is produced by the optical amplifiers used, at the intermediate nodes, as repeaters, or as preamplifier before the receiver. It is quantified in terms of noise figure which represent how much higher the noise power spectral density of the amplified output is compared with input noise power spectral density times the amplification factor and is often specified in decibels (dB). Amplifiers emit noise (ASE) in both forward and backward direction, but only the forward noise will co-propagate with the signal to the receiver where it degrades the system performance. Counter propagating noise limits the achievable gain of the amplifier and increases the noise level. Its effect can be reduced by increasing the input lase intensity, tuning the master oscillator so that it is resonant with the amplifier, or by decreasing the amplifier facet reflectivities.

F) Polarization Dependent Loss

The two polarization components along the two axes of a circular fibre suffers different rates of loss due to irregularities in the fibre, there by degrading signal quality in an uncontrolled and unpredictable manner and introducing fluctuations in optical signal to noise ratio. It is measure of the peak-to-peak deference in transmission of an optical system with respect to all possible states of polarization and is given by

$$PDL_{dB} = 10. log \frac{P_{max}}{P_{min}} \tag{2.4}$$

Where P_{max}, P_{min} are the maximum and minimum output power. It mainly occurs in passive optical components. It is measured by polarization scanning techniques or by Muller matrix method.

G) Crosstalk

It arises due to incomplete isolation of WDM channel by optical components such as OADMs, OXCs, multiplexer/de-multiplexer and optical switches. We can say in a simple sense it occurs due to leakage of power from other WDM channels on the desired channel. There are some other sources of crosstalk like FWM, cross-phase modulation and stimulated Raman scattering, which we will discuss in the latter sections. Linear crosstalk can be either incoherent (out-band) or coherent (in-band). In-band crosstalk has very adverse effect in comparison to out-band crosstalk as it lies in the same nominal wavelength as the desired signal. Fig.2.4 shows how crosstalk arises during switching. In our work we mainly focused on in-band crosstalk and detail mathematical model are given in chapter 3.

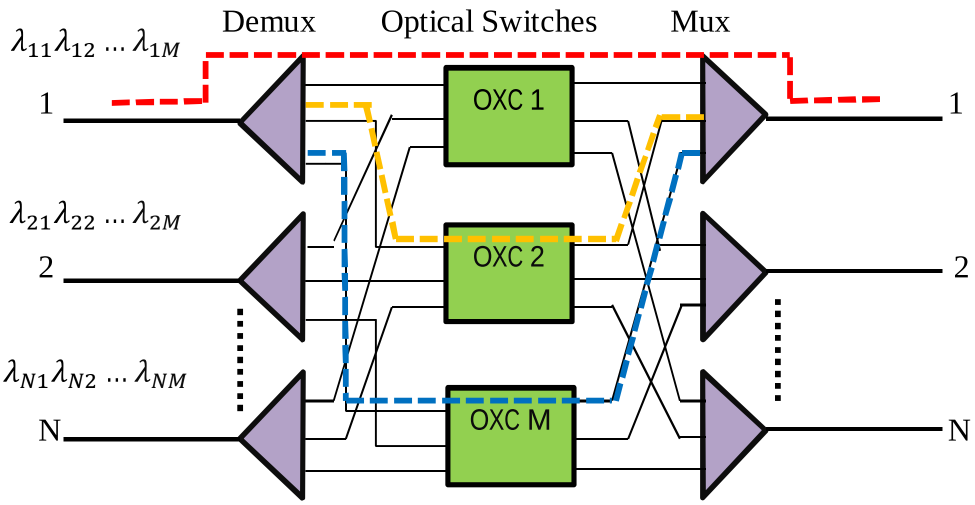

Fig. 2.8 Structure of a typical OXC with N ports and M wavelength

2.5.2 Non-linear Impairments

A) Self-Phase Modulation:

It arises due to variation of refractive index of the fibre with intensity of the signal. An induced phase-shift occurs due to these variations and thus, different part of the pulse undergo different phase shift and gives rise to chirping of the pulses. This chirping enhances the pulse broadening effect (in frequency domain) of chromatic dispersion. These effects are more profound in systems transmitting high power (especially in long-haul communication). Systems operating above 10Gbps or systems having slow data rate but high transmitting power, SPM significantly increases the pulse broadening effect of chromatic dispersion. The chirp also depends on the input pulse shape. Generally the chirped RZ modulation reduces the effect of SPM.

B) Cross-Phase Modulation:

The variation of refractive index of the fibre not only depends on the intensity of the pulse but also on the intensity of the other co-propagating optical pulses. The fluctuation in the intensity of other pulses causes phase modulation of the pulse and it is called as XPM. It results asymmetric spectral broadening and distortion of the pulse shape. It has more adverse effect than SPM and influences it severely when the numbers of channels in the fibre are high. The cross-phase modulation induced phase shift occurs when two pulses overlap in time. Due to this overlapping, the chirping get enhanced leading to pulse broadening. Its effect can be reduced by increasing the wavelength spacing between the channels or by care full selection of bit rate for adjacent channels that are not equal to the present channels.

C) Four Wave Mixing:

For a WDM/DWDM system operating at frequencies $f_1, f_2, \ldots f_n$, the variation of refractive index not only induces phase shifts within the channel but also give rise to signals at new frequencies such as $2f_i - f_j$ and $f_i + f_j - f_k$. In comparison to self and cross phase modulation, four wave mixing effect is independent of the bit rate of the system but is critically dependent on the channel spacing and chromatic dispersion of the fibre. Four wave mixing effect increases as the channel spacing decreases. Its effect has to be considered even when the data rate is moderate and when dispersion shifted fibre are used. In general for W wavelength launched into a fibre, the number of four wave channel produced is $W^2 (W-1)/2$. In our work we take FWM into our consideration and details of it are given in the chapter 3.

D) Stimulated Raman Scattering:

When two or more optical signals at different wavelengths are injected into a fibre, the SRS causes optical power from lower wavelength channels to be transferred to the higher wavelength channels. This can skew the optical power distribution among the WDM channels reducing the SNR of the lower wavelength channels and introducing crosstalk on higher wavelength channels. Both of these effects reduce significantly the data carrying capacity of the fibre. It occurs at higher optical power than stimulated brillouin scattering. It scatters in both forward and backward direction. SRS effect can be reduced by using optical filtering techniques.

E) Stimulated Brillouin Scattering:

It is the most dominant fibre non-linear scattering s effect. Stimulated brillouin scattering occurs when an optical signal in the fibre interact with the acoustic phonons. This interaction occurs over a very narrow line width. The scattering process is stimulated by photons with a wavelength higher than the wavelength of the incident signal. It sets an upper limit on the amount of optical power that can be launched into an optical fibre. When input power exceeds the threshold value, a significant amount of transmitted light is redirected back to the transmitter leading to saturation of optical power in the receiver, and introduces noise that degrades the system performance.

2.6 Crosstalk

In high-capacity optical networks, many wavelength channels are deployed with data rate of 10Gbit/sec or even higher per channel. In order to fulfil the required information capacity, the number of wavelength per channel in an optical fibre has to be very large, but it is limited by the bandwidth of the optical devices, such as optical amplifier. In order to make the entire available wavelength to be within the amplifier bandwidth, we have to make the wavelength channel as close as possible.

These closely spaced wavelength channels results system impairments when optical wavelength selective components along the light path are not able to distinguish the closely-spaced wavelength channels [13, 14, 15] . Crosstalk also arises when the combined optical power of the wavelength channels is so high that the optical fibre can no longer be treated as a linear medium. Crosstalk results a significant degradation of signal quality and should be taken into account during routing and wavelength assignment. In literature, different types of optical crosstalk in a transmission system are considered and they are given in the next section.

2.7 Types of Crosstalk

Optical crosstalk can be broadly classified into non-linear and linear types. Figure 3.1 shows different types of crosstalk that arises in a WDM/DWDM network. For high optical power, the refractive index of a fibre will depend on the optical intensity of signals propagating through the fibre. Generally in most of the time we employed intensity modulation (OOK) for our optical transmission, so that the intensity of optical signal under goes a constant fluctuation. This fluctuation causes changes in the refractive index of the fibre [13], which results phase variation in between the wavelength channels. As a result, optical crosstalk of the type cross-phase modulation and four wave mixing arises, which may impair system performance.

In our work we only take four wave mixing into our consideration. Linear crosstalk is caused entirely by non-ideal performance of the optical components, such as OXC and OADM. Figure 3.2 shows a schematic representation of how linear crosstalk arises due to non-ideal nature of optical cross switches.

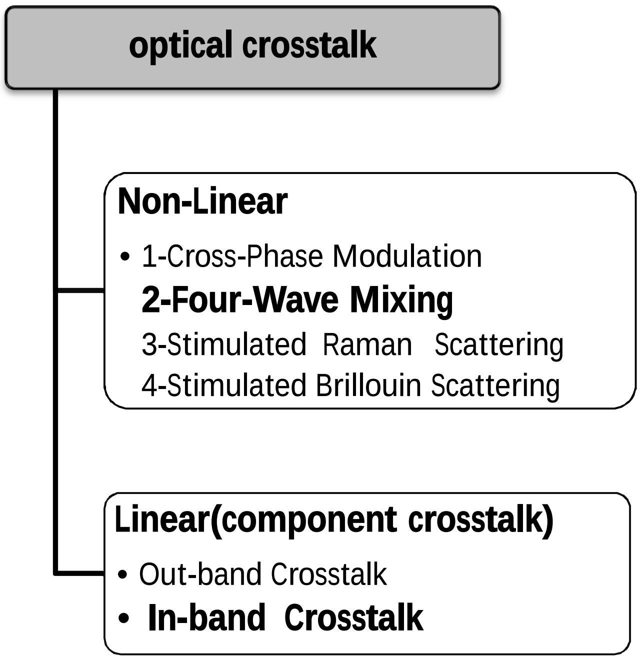

Fig. 3.1 Different types of optical crosstalk in WDM/DWDM network

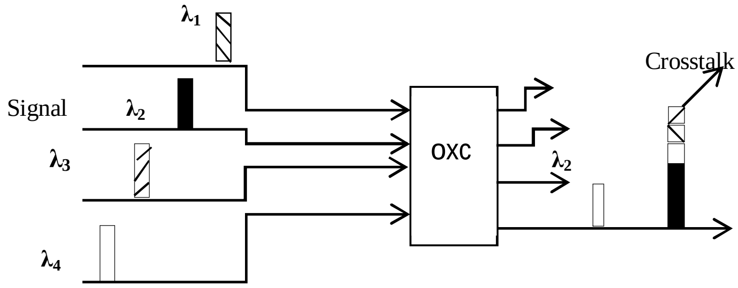

Fig.3.2 Example showing how in-band crosstalk is induced in optical network

2.8 Component Crosstalk

Component crosstalk is one of the major physical layer impairment that arises due to non-ideal nature of optical add-drop multiplexer & cross switches used in modern optical networks. Linear crosstalk in optical components can be classified as in-band or inter-band crosstalk [17] depending on whether it has the same nominal wavelength as the desired signal or not.

The effect of inter band crosstalk can be reduced by concatenating narrow-bandwidth optical filters. In-band crosstalk however cannot be removed as the signal and the crosstalk operates at same wavelength. The deteriorating effect of in-band crosstalk is further intensified in cascaded optical node due to its accumulative behavior [13, 14, 15]. These interferences limits system performance as network expands and wavelength density increases. In-band crosstalk causes the quality of optical signal to degrade and become so poor that its BER is unacceptably high. Conventional studies on routing and wavelength assignment has proposed many algorithms for establishing LPs without considering any physical layer impairments [24]. In last few years, RWA techniques that consider quality of transmission (QoT), as measured by BER, have been the subject of intense research [3, 5, 6]. Here we proposed a QoT guaranteed algorithm that perform conventional RWA and allow the selected LPs to be established if the BER requirement is met.

BER at the receiver is evaluated by calculating the noise in the photo detector output due to crosstalk and the noise of the detector itself. In many cases the probability density function of the overall noise is assumed to be Gaussian due to its simplicity. However, the Gaussian model, despite of its simplicity, cannot accurately describe the signal crosstalk noise, especially when the no of interfering channels is not very large. Though central limit theorem is a good reason to use Gaussian approximation for reasonable large number of crosstalk [13, 14], but for a small size mesh or ring network where no of crosstalk element are small this approximation gives inaccurate results. Therefore several non-Gaussian models are developed for better estimate of system performance. The pdf of non-Gaussian models developed for finite interference uses different techniques, such as saddle point approximation[19],moment generating function[18],Gram-Charlier series [17] and modified chernoff bound [20].However these are often computationally complex and take more time to evaluate BER during data path selection. Here we have followed a simplified approach for BER calculation based on Taylor series expansions as given in [13, 14].

Table 2.1

Author and References	Model used	Complexity Level	RWA Schemes	Remarks
Sarah D. Dods et al. [13]	Taylor Series Expansions	Medium	Not Considered	Accurate model for low level crosstalk
Keang-po Ho [17]	Gram-Charlier Series	High	Not Considered	A Correction to Gaussian Approximation But Computationally it takes a large time during the connection provisioning
Idelfonso Tafur Monroy et al. [19]	Saddlepoint Approximation	High	Not Considered	-do-
Jun He et al. [15]	Gaussian Approximation	Low	Considered	It is the simplest approach but Gaussian Approximation is found to be overestimate the system degradation especially when no of crosstalk components are low
Santu Sarakar et al. [14]	Taylor Series Expansions following a simplified approach	Low	Not Considered	Accurate and Simple Model for low level of crosstalk and computationally it take less time during light path set up
Our Proposed work	-do-	Low	Considered	A Simple Approach for Routing and Wavelength Assignment , Which is Computationally Easy and Provides the Guaranteed QoT on the Prescribed Light path

Chapter -3

Crosstalk in WDM/DWDM Networks

Types of Crosstalk

Component Crosstalk

In-band Crosstalk

3.1 In-band Crosstalk Model

In WDM/DWDM network a message is sent from one node to another node using a wavelength continuous route called light paths (LPs) without requiring any O-E-O conversion and buffering at the routing node. Multiplexing, de-multiplexing and switching are done in the optical domain using prisms and diffraction gratings. Non-ideal nature of these component results in-band crosstalk, which has the same wavelength as the signal and degrades the transmission performance of the network. In-band crosstalk can be divided into coherent crosstalk, whose phase is correlated with the desired signal considered, and incoherent crosstalk whose phase is not correlated with the signal considered [19].

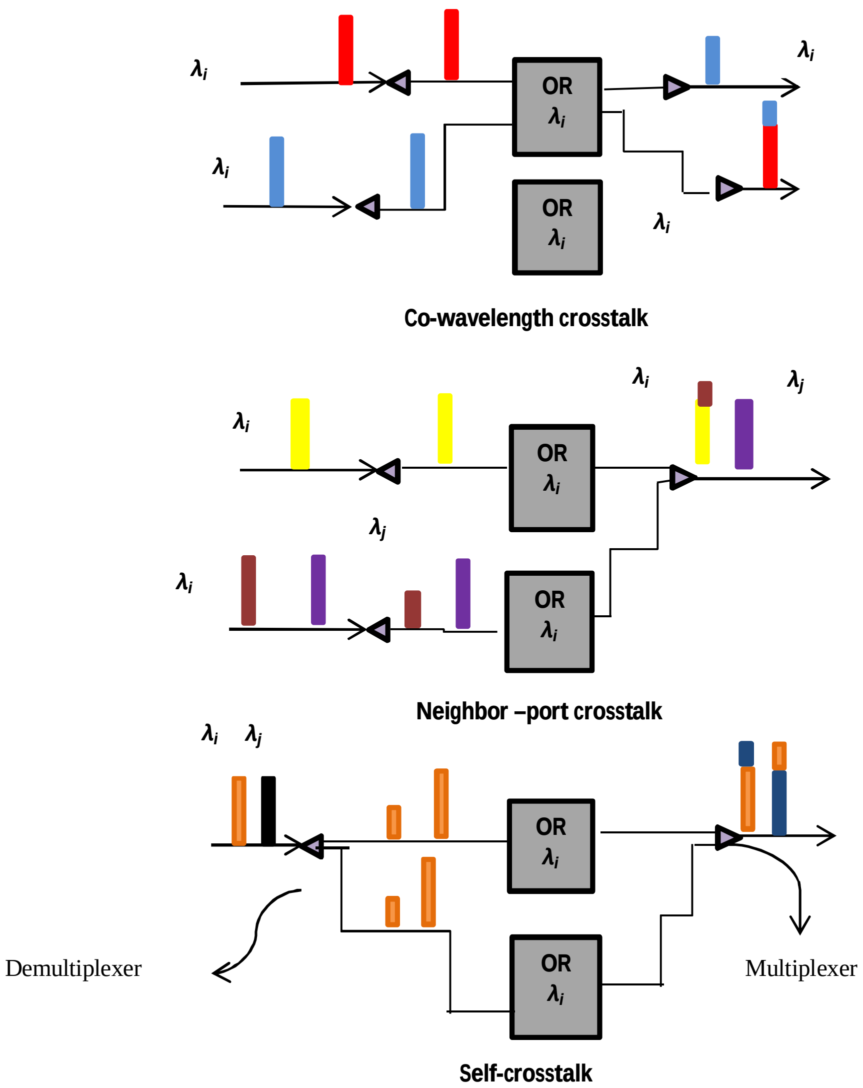

Fig.3.1 Example showing how different types of in-band crosstalk are induced in optical WDM network, OR: Optical Router

Coherent crosstalk is believed not to cause noise but causes small fluctuation of signal power. In this paper, we considered in-coherent crosstalk which has the more adverse effect than coherent crosstalk.Fig.1 shows origin of different type of in-band crosstalk such as co-wavelength crosstalk (ideal case), neighbor port crosstalk and self-crosstalk. In ideal case there will be no crosstalk as two signals (with wavelengths λ_i and λ_j) are routed to different output ports. However in other two cases, any leaking or in sufficient isolation may induced homodyne crosstalk.

Incoherent crosstalk is often analyzed using the *pdf* of the noise in the received photocurrent. The *pdf* can be derived from the fields of the wanted signal and of each interfering signal. Desired optical signal and each interfering signal is assumed to be

$$E_S(t) = \overrightarrow{r_s}\, b_s(t)\sqrt{p_s}\exp[(j\omega_s t + j\phi_s(t))] \tag{3.1}$$

$$E_{\varepsilon k}(t) = \overrightarrow{r_k}\, b_k(t)\sqrt{\varepsilon_k p_s}\exp[(j\omega_s t + j\phi_k(t))] \tag{3.2}$$

Where all fields have the same nominal optical frequency ω, $\phi(t)$ represent the independent phase fluctuation of each optical source, p_s is the optical power in the desire signal, and ε_k is the optical power of the k_{th} interference relative to the signal. $b_{s,\,k(t)}$ $=0,1$ depending on whether zero or one is transmitted by the desired and interference signal at time t. The total incident optical field on the photo detector can be written as for N crosstalk term

$$E_{ph}(t) = E_S(t) + \sum_{k=1}^{N} E_{\varepsilon k}(t) \tag{3.3}$$

$$E_{ph}(t) = \overrightarrow{r_s} b_s(t)\sqrt{p_s}\, exp\,[(j\omega_s t + j\phi_s(t)] \sum_{k=1}^{N} \overrightarrow{r_k}\, b_k(t)\sqrt{\varepsilon_k p_s} exp\,[(j\omega_s t + j\phi_k(t)] \tag{3.4}$$

For unit detector responsivity and for worst-case assumption of identical polarization of signal and crosstalk, the photo current *i(t)* is given by

$$i_{ph}(t) = \left|E_{ph}(t)\right|^2$$

$$i_{ph}(t) = b_S^2(t)p_s + 2p_s \sum_{k=1}^{N} b_s(t)b_k(t)\sqrt{\varepsilon_k} cos\theta_k(t) + p_s \sum_{k=1}^{N} b_k^2(t)\varepsilon_k \tag{3.5}$$

Where $\theta_k(t) = \phi_k(t) - \phi_s(t)$, $k=1,\ldots,N$, are random phase. Ignoring the small terms in the order of ε_k, the overall receiver noise in the photodetector is

$$n(t) = 2p_s \sum_{k=1}^{N} b_s(t)b_k(t)\sqrt{\varepsilon_k} cos\theta_k(t) + n_g(t) \tag{3.6}$$

When ZERO is transmitted by the signal channel, there is no crosstalk and noise $n_0(t) = n_g(t)$, where $n_g(t)$ is the usual Gaussian noise in the receiver. When ONE is transmitted by the signal channel crosstalk generates a total noise

$$n_1(t) = 2p_s \sum_{k=1}^{N} b_k(t)\sqrt{\varepsilon_k} cos\theta_k(t) + n_g(t) \tag{3.7}$$

For N interferers and Gaussian noise, the *pdf* of the noise in the received photocurrent can be obtained by integrating the Gaussian noise over all possible values of phase offset between signal and each interferences [13, 14]. Assuming the phase difference between signal and interferers are independent and uniformly distributed between $(0, \pi)$, the noise photocurrent *pdf* is given by

$$p_{nk}(y) = \frac{1}{\sqrt{2\pi\sigma}\pi^N} \times \left[\int_0^{\pi} .. \int_0^{\pi} exp\left\{-\frac{\left(y-\sum_{k=1}^{N} A_K cos\theta_k\right)^2}{2\sigma^2}\right\}\right] d(\theta_1) \ldots d(\theta_N) \tag{3.8}$$

Where $A_k=2\sqrt{\varepsilon_k}p_s$ and σ is the variance of thermal noise. The effect of crosstalk is maximum when phase difference is close to 0 and the *pdf* can be approximated by expanding the cosine term by first order Taylor series [13] up to the term θ_k^{2}.

$$p_{nk}(y) = \frac{1}{\sqrt{2\pi\sigma}\pi^N} \times \left[\int_0^{\pi} .. \int_0^{\pi} exp\left[-\frac{\left\{y-\sum_{k=1}^{N} A_K\left(1-\frac{\theta_k^2}{2}\right)\right\}^2}{2\sigma^2}\right]\right] d(\theta_1) .. d(\theta_N) \tag{3.9}$$

Expanding the square term and keeping term upto θ_k^2, the the *pdf* for noise when signal is transmitting 1 is given by

$$p_{nk}(y) = \frac{1}{\sqrt{2\pi\sigma}} \left\{\prod_{k=1}^{N} f(y)\right\} exp\left[-\frac{(y-\sum_{k=1}^{N} A_K)^2}{2\sigma^2}\right] \tag{3.10}$$

Where

$$f(y) = \sqrt{\frac{\sigma^2}{2\pi A_k\left(y-\sum_{k=1}^{N} A_k\right)}}\, erf\left[\pi\sqrt{\frac{A_k(y-\sum_{k=1}^{N} A_k)}{2\sigma^2}}\right] \tag{3.11}$$

BER in the presence of in-band crosstalk is given by fraction of the received photocurrent *pdf's* that fall on the wrong side of some decision variable d, for each combination of data "1"s and "0" of the signal and crosstalk. Here we fallowed a simplified approach as given by Santu sarkar and et al. [14] for extreme case when all interferers are transmitting "1", so that we have an upper bound for BER during our routing and wavelength assignment algorithm.

$$p_e = \frac{1}{2}p_{e0} + \frac{1}{2}\left[\frac{1}{2}p_{e1(b_k=0)} + \frac{1}{2}p_{e1(b_k=1)}\right] \quad (3.12)$$

Where $p_{e0} = \frac{1}{2}erfc\left(\frac{d}{\sqrt{2\sigma_{th}{}^2}}\right)$

$$p_{e1}(b_k = 0) = \frac{1}{2}erfc\left(\frac{I_S - d}{\sqrt{2\sigma_{th}{}^2}}\right)$$

$$p_{e1}(b_k = 1) = \frac{1}{2^{N+1}}\left\{\prod_{k=1}^{N} f(I_S - d)\right\}\sum_{k=1}^{N} erfc\left\{\frac{(I_S - \sum_{k=1}^{N} A_k)}{\sqrt{2\sigma^2}}\right\}$$

Here the weighting function *f(y)* is approximated as $f(I_s - d))$ to make the integral possible. σ^2 is the variance of the receiver noise when "1" is transmitted by the signal channel and σ_{th}^2 is the variance of the receiver thermal noise when "0" is transmitted. Expression for BER at the WDM receiver is given by [2].

$$p_e = \frac{1}{4}erfc\left(\frac{d}{\sqrt{2\sigma_{th}{}^2}}\right) + \frac{1}{8}erfc\left(\frac{I_s - d}{\sqrt{2\sigma_{th}{}^2}}\right) + \frac{1}{2^{N+3}}\left\{\prod_{k=1}^{N} f(I_s - d)\right\}\sum_{k=1}^{N} erfc\left\{\frac{(I_S - \sum_{k=1}^{N} A_k)}{\sqrt{2\sigma^2}}\right\} \quad (3.13)$$

From the above equation power penalty is found by comparing the photocurrent at the receiver that produces the same BER with and without crosstalk.

$$PP = 10log\left(\frac{I_S{}'}{I_s}\right) \quad (3.14)$$

3.2 BER Constrained Data Path Selection Algorithm

Mitigating the effects of crosstalk in all optical networks is a difficult task because crosstalk lies in the same band as the desired signal and therefore cannot be filtered. But by selecting appropriate connection used by a request in a network at connection arrival time, it is possible to minimize the impact of crosstalk. BER constrained datapath selection is a technique where the choice of a datapath depends on the network state as opposed to static schemes where selection is fixed.

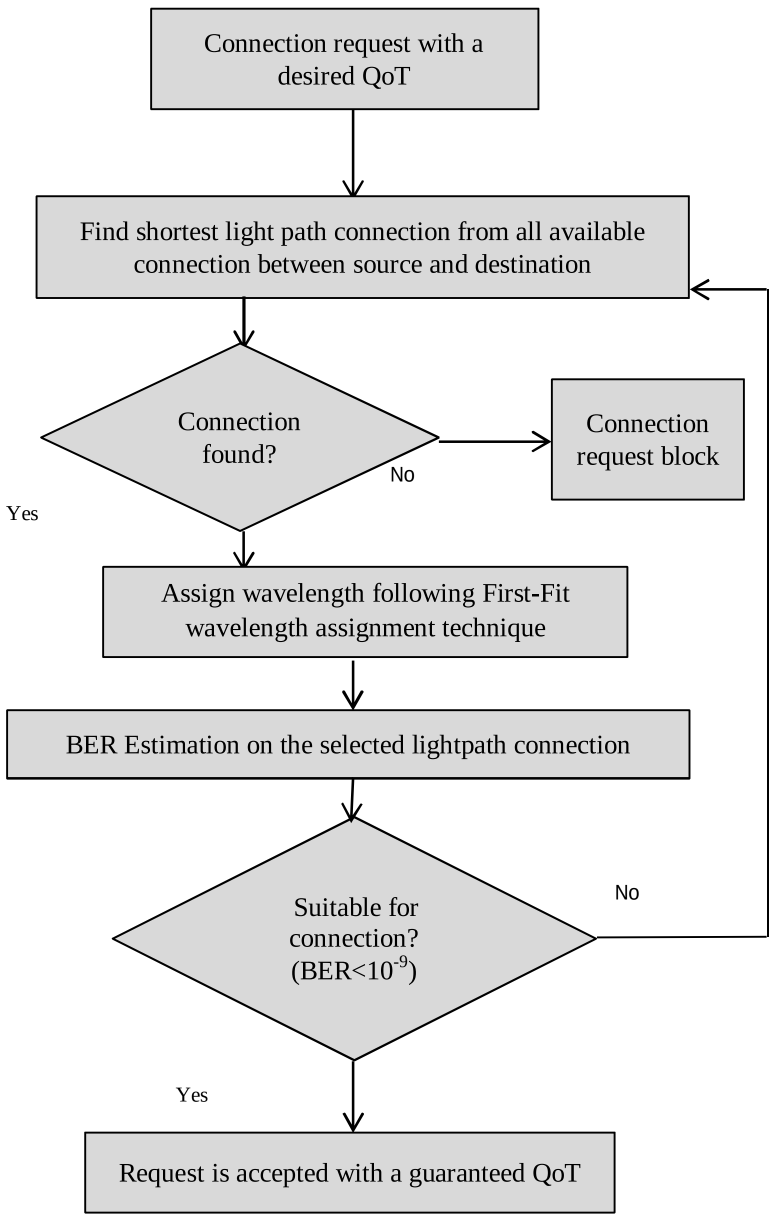

Fig. 3.2 Flowchart of BER constrained based RWA algorithm

Fig. 3.2 shows the algorithm for the selection of datapath selection from a particular source to destination. A lightpath is assigned if and only if BER constrain is satisfied. We also include FWM wavelength assignment scheme in our algorithm as given in [28]. Here we assumed that the maximum bit error rate should not be higher than 10^{-9}.

3.3 FWM induced Crosstalk

We have already discussed about four wave mixing in chapter 2. In this chapter we discuss the mathematical model of FWM induced crosstalk and also discuss their impact on the network performance. It occurs when two or more signals of different wavelength are propagating simultaneously; interact with the nonlinear dielectric fibre medium and generates a set of new frequencies within the operating frequencies [27]. FWM does not depend on bit rate. It is always present in an optical network but they became prominent in new generation optical networks because of following main reasons.

- Use of high intensity signal
- High density channels
- Use of low chromatic dispersion shifted fibre

Equally spaced channel f_i, f_j and f_k results FWM components at frequencies given by

$$f_{ijk} = f_i + f_j - f_k \quad provided\ that\ i \neq k, j \neq k. \tag{3.15}$$

The newly generated frequencies lie within the operating frequency spectrum and can affect network performance due to in-band crosstalk generation and power reduction in the same nominal frequency. No of FWM components generated is given by

$$N = n(n-1)^2 \tag{3.16}$$

For example if we assume 3 wavelengths are present and the centre wavelength is 193.1 THz with frequency spacing 25 GHz, then the no of FWM component generated are given in fig. 3.3.

The power of a FWM product is given by [27].

$$p_{ijk} = \frac{\eta}{9} D^2 \gamma^2 p_i p_j p_k e^{-\alpha L} \left[\frac{\left(1-e^{-\alpha L}\right)^2}{\alpha^2} \right] \tag{3.17}$$

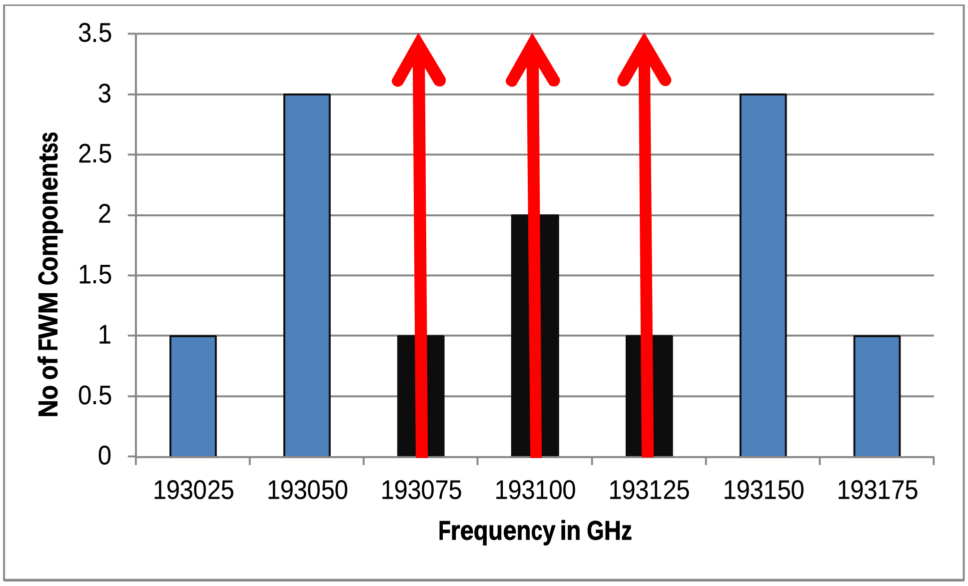

Fig. 3.3 FWM components generated for three equally spaced channel

Where, D is the degeneracy factor, γ is the non-linear coefficient calculated from the refractive index and diameter of the fibre and p_i, p_j, p_k are the input power at the respective frequencies. L is the fibre length and α is the fibre attenuation coefficient.

The FWM light is detected at the receiver together with the signal light, and induces noise which is given by [30]

$$N_{FDM} = 2b^2 p_s \frac{p_{ijk}}{8} \tag{3.18}$$

Where b is the receiver's responsivity and p_s is the channel power at the receivers input.

This noise results BER at the receiver which can be expressed as

$$p_e = \frac{1}{4} erfc\left(\frac{d}{\sqrt{2{\sigma_{th}}^2}}\right) + \frac{1}{8} erfc\left(\frac{I_s - d}{\sqrt{2{\sigma_{th}}^2}}\right) + \frac{1}{2^{N+3}}\left\{\prod_{k=1}^{N} f(I_s - d)\right\}\sum_{k=1}^{N} erfc\left\{\frac{(I_S - \sum_{k=1}^{N} A_k)}{\sqrt{2(\sigma^2 + N_{FWM})}}\right\} \tag{3.19}$$

Here we have assumed that the FWM components are present only when all the co-propagating channels are transmitting bit one.

3.4 FWM aware wavelength assignment scheme

We have seen in the last section that FWM results crosstalk. It is assumed that at the starting point of a light path crosstalk is zero and it accumulates along the route of the light path. At the end of the light path the total induced crosstalk is given by the contribution from the individual section. When a light propagates through several concatenated fibre link it may encounter different co-propagating lightpath and experiences different FWM crosstalk component in the different link. Hence the FWM induced crosstalk depends upon the dynamic state of the network [28]. As shown in fig.3.2 induced crosstalk affect significantly the wavelengths present at the centre of our transmission window, rather than the wavelengths present on the either side of the window. In order to avoid this effect WDM channels are designed with unequal channel spacing. No doubt this method results FWM components at different frequencies that does not interfere with the existing lightpaths, but the major problem is that the transmission window broadens to accommodate all channel.

In a fibre, we have other sources of impairments like switch crosstalk, ASE, shot noise and thermal noise other than FWM noise. In some situation the contribution from other noise source may dominate the FWM induced noise. Hence unequal channel spacing is not a good option where we are sacrificing transmission bandwidth. In our work, we have followed a wavelength assignment scheme contributed by Aneek Adhya et. al [28, 31]. We have done a slight modification to that wavelength assignment scheme and incorporate into our BERC algorithm. The result shows an enhancement of overall network performance. Here the entire transmission window has been divided into two segments an outer segment and an inner segments. The outer segment is reserved for the light path that has to be travel a longer distance and inner segment is reserved for smaller distance covered light paths.

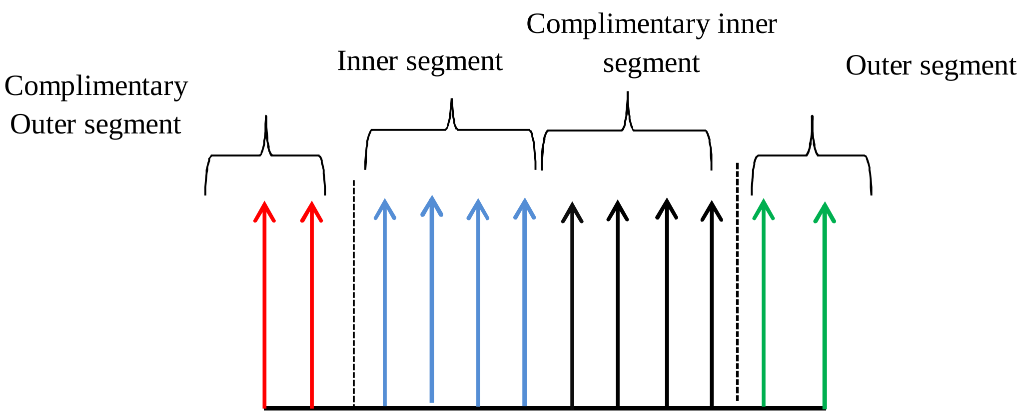

Fig.3.4 Division of transmission window for long and short lightpath

Our proposed BER constrained FWM aware RWA algorithm is given in fig.3.5.

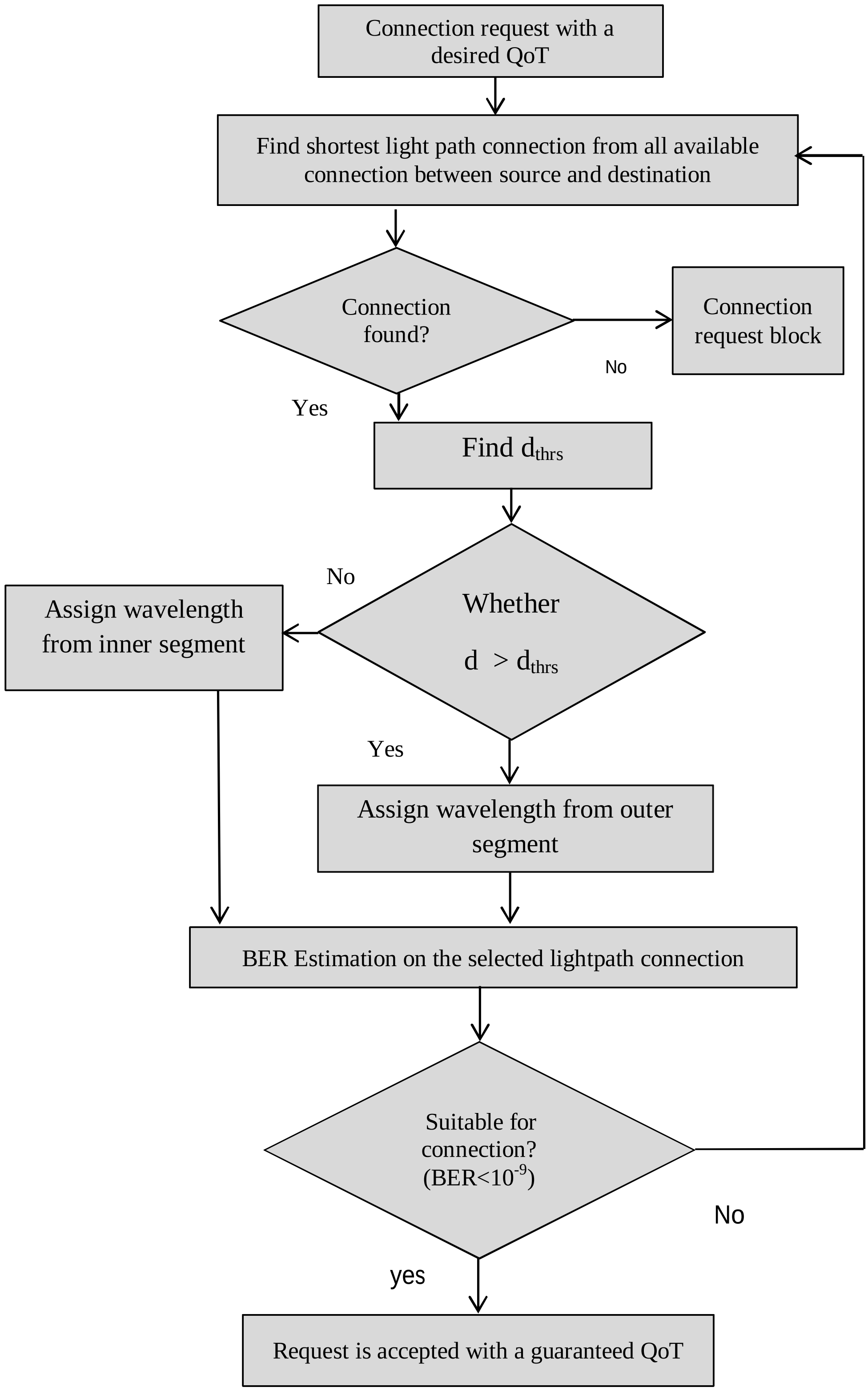

Fig. 3.5 Flowchart of BER constrained FWM aware RWA algorithm

Chapter -4

Simulation and Results

BERC Algorithm

Topology

Blocking Probability

4.1 Simulation and Result

In this chapter we discuss the simulation result for an optimal lightpath selection mechanism based on a guaranteed QoT, as described in the earlier chapter. We use MATLAB for our simulation works. We have also shown the impacts of component crosstalk and FWM crosstalk on signal quality through simulations.

4.2 Impact of component crosstalk and FWM crosstalk

The performance degradation due to in-band crosstalk depends very much on the no of crosstalk interferences. In fig. 4.1 the BER is plotted as a function of input power for different number of interfering channels (N). This figure shows that BER increases significantly as the no of crosstalk component increases. Here we have neglected the effect of shot noise and assumed that all interferers have same amount of crosstalk level. During simulation we take several parameters into consideration and their values [27] are given in table 4.1.

In fig.4.2 we have shown variation of power penalty as a function of crosstalk level for different no of interfering channel. Power penalty increases very rapidly as crosstalk level increases as well as the no of interfering channel increases.

Table 4.1

Parameters	**value**
Receiver's responsivity	1
Extinction ratio	infinity
Thermal noise	0.05mA
Detection threshold	½(p_i)
Input power	3mw
Fiber attenuation	0.2 dB/km
Nonlinear coefficient γ	2.35$(w.km)^{-1}$

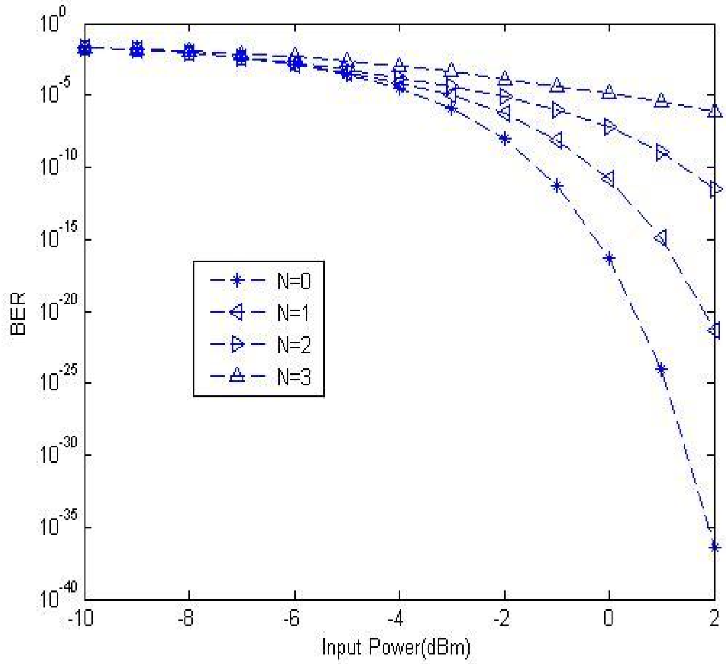

Fig. 4.1 Plot of BER with the input power for different number of interfering channel

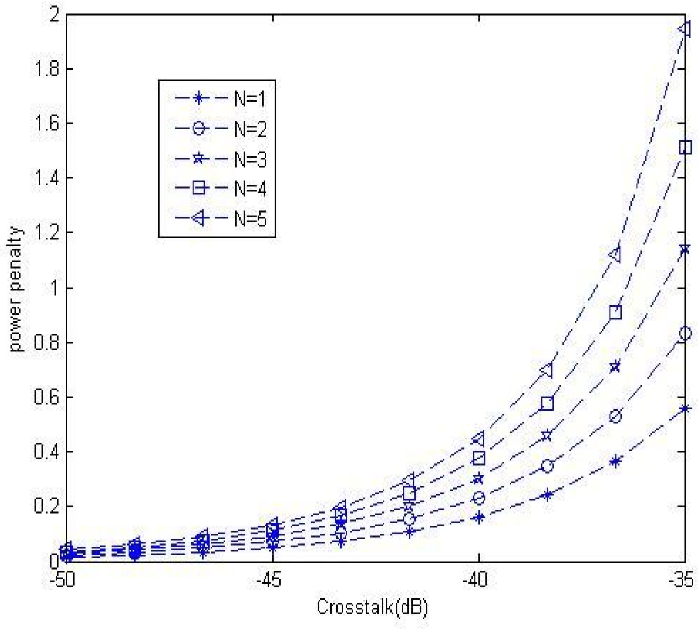

Fig. 4.2 Variation of power penalty with crosstalk level for different number of interfering channel

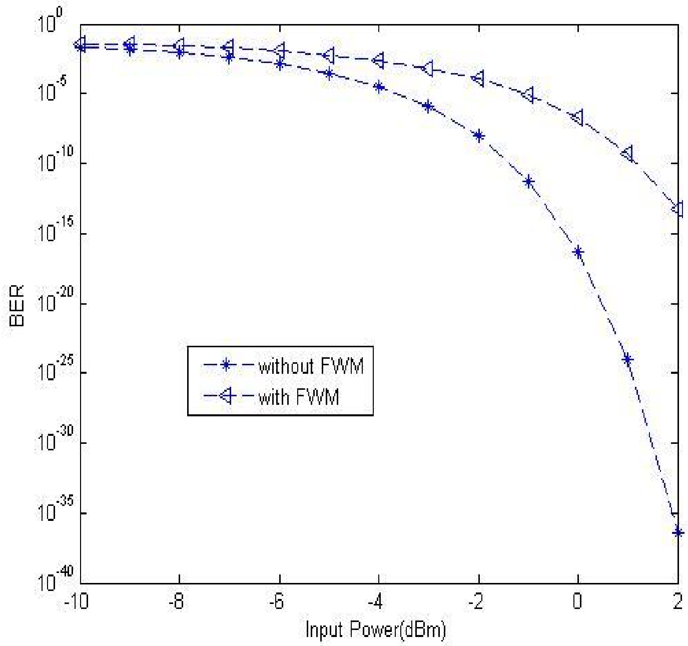

Fig. 4.3 Plot of BER with the input power for 3 FWM active components

4.3 Simulated Topology

We consider the optimal datapath selection mechanism based on minimum BER constrained BERC algorithm. The performance degradation due to in-band crosstalk depends very much on the no of crosstalk interferences.

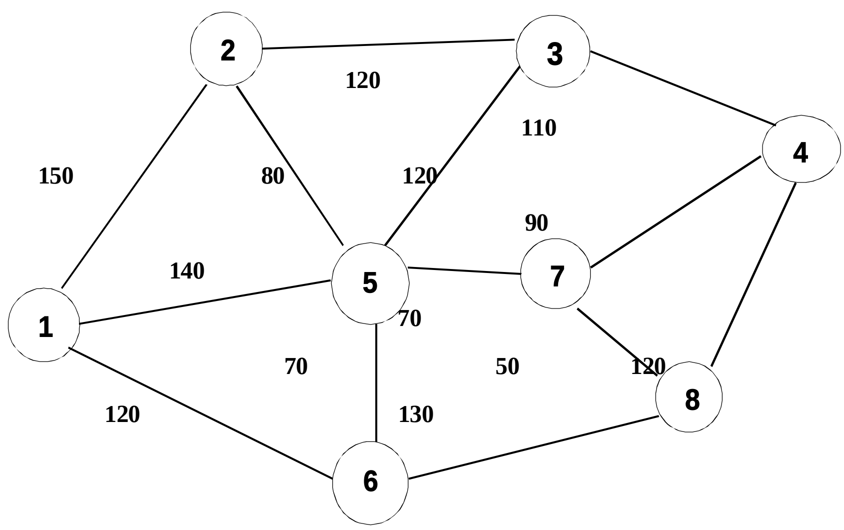

Fig.4.4 A sample mesh network with fiber length (in km) marked on each link

We evaluated our algorithm on an 8 node topology given in Fig.4.3 as the example of physical topology. Each fiber in the physical topology has 6 wavelengths per link and we assumed that every node is reachable from every other node. Here we also assume that no node has wavelength conversion capability and all the lightpaths should satisfy wavelength continuity constrain.

We considered different static traffic matrix and analyze the given topology. The matrix elements are considered as the representative traffic flow between respective node pairs. Table 4.2 show one of the randomly taken traffic matrix indicating the source and destination with number of lightpaths to be established between them. First we analyze our algorithm with First- Fit wavelength assignment scheme and then with FWM aware wavelength assignment scheme.

S/D	1	2	3	4	5	6	7	8
1	0	0	1	0	2	1	1	0
2	2	0	0	0	0	0	1	1
3	1	0	0	0	0	2	0	0
4	0	1	0	0	0	0	0	1
5	0	0	0	1	0	0	0	0
6	1	0	0	1	0	0	0	0
7	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	1	0

Fig. 4.5 A Traffic Matrix indicating the no of connection to be made between a particular source and destination

4.4 Simulation result for BER constrained based algorithm

Fig.4.4 shows the topology with existing connections using different colors for different wavelength, satisfying wavelength continuity constrain as given by the traffic matrix. Now if we want to set up a connection between A and D, the traditional shortest path (for routing) and first-fit (for wavelength assignment) algorithm will select the path 1-5-7-4, which is the path with maximum number of crosstalk. Then we apply our BERC algorithm with First-Fit aware wavelength assignment scheme, and our algorithm will select the path 1-2-3-4, which has less no of crosstalk component as compared to the previous one.

We have plotted the BER for both the light paths as given in Fig. 4.5. Figure clearly shows lightpath selected by BERC algorithm has better QoT than traditional shortest algorithm. The demerit of this algorithm is that, sometimes it will choose a path that has larger distance (delay) as compared to shortest-path algorithm. But the use of delay compensated fiber will minimize the effect ant QoT of transmission in terms of BER is satisfied.

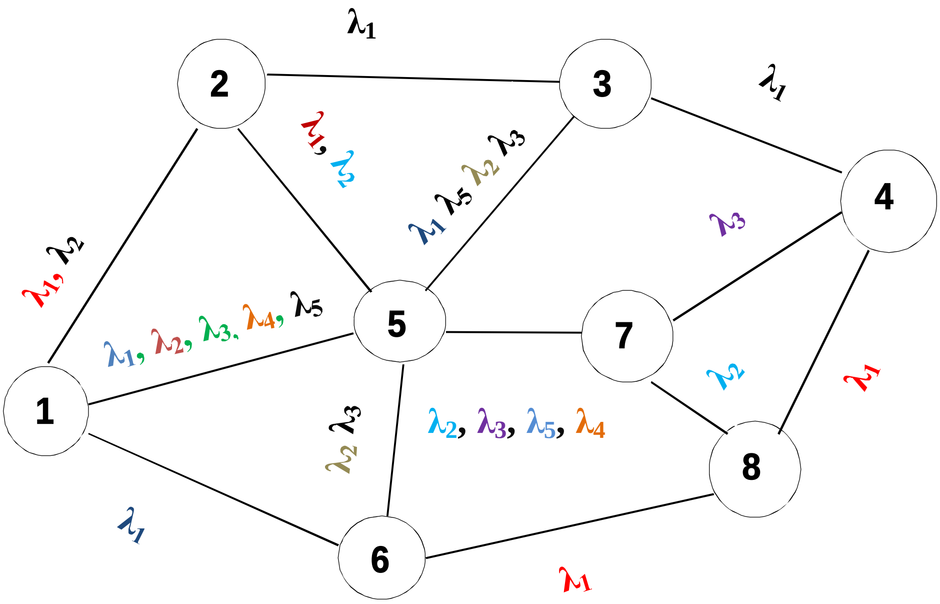

Fig.4.6 Network showing the existing connection using different color for different wavelengths followed by first-fit wavelength assignment scheme.

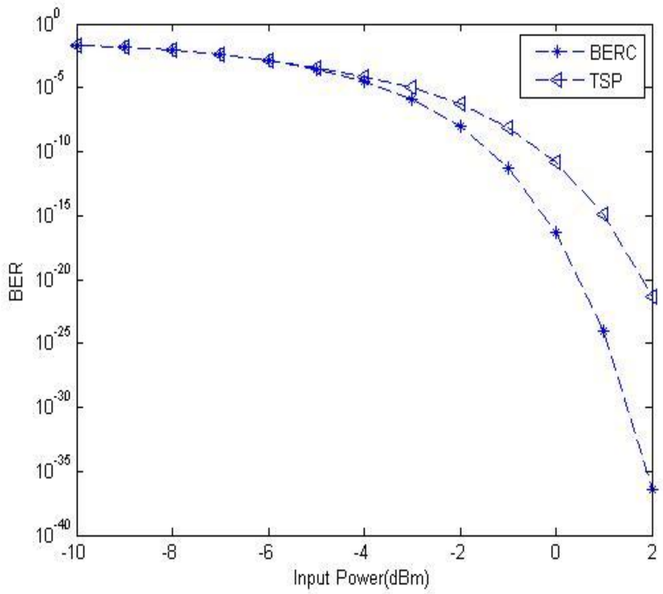

Fig. 4.7 Plot of BER for the path selected by traditional shortest path (TSP) & our BERC algorithm

For the same topology we have computed three pair of source and destination and their possible paths to choose an optimum path which has the minimum BER. For this simulation we did not take FWM into our consideration.

Source/ Destination	Possible Path	Path Ref. No	BER	Optimum Path
1-4	1-5-7-4	1	10^{-3}	1-6-8-4
	1-5-3-4	2	10^{-7}	
	1-2-3-4	3	10^{-13}	
	1-6-8-4	4	10^{-17}	
2-8	2-5-7-8	1	10^{-3}	2-1-6-8
	2-5-6-8	2	10^{-13}	
	2-3-4-8	3	10^{-10}	
	2-1-6-8	4	10^{-17}	
6-7	6-5-7	1	10^{-10}	6-8-7
	6-8-7	2	10^{-13}	
	6-8-4-7	3	10^{-13}	
	6-1-5-7	4	10^{-7}	

Table 4.2 Simulation result for optimal path selection

Fig. 4.6 shows the graphical representation of best-lightpath based on BER estimation for each path of different source-destination pair. The path corresponding to minimum BER for a source and destination pair is the optimal light path.

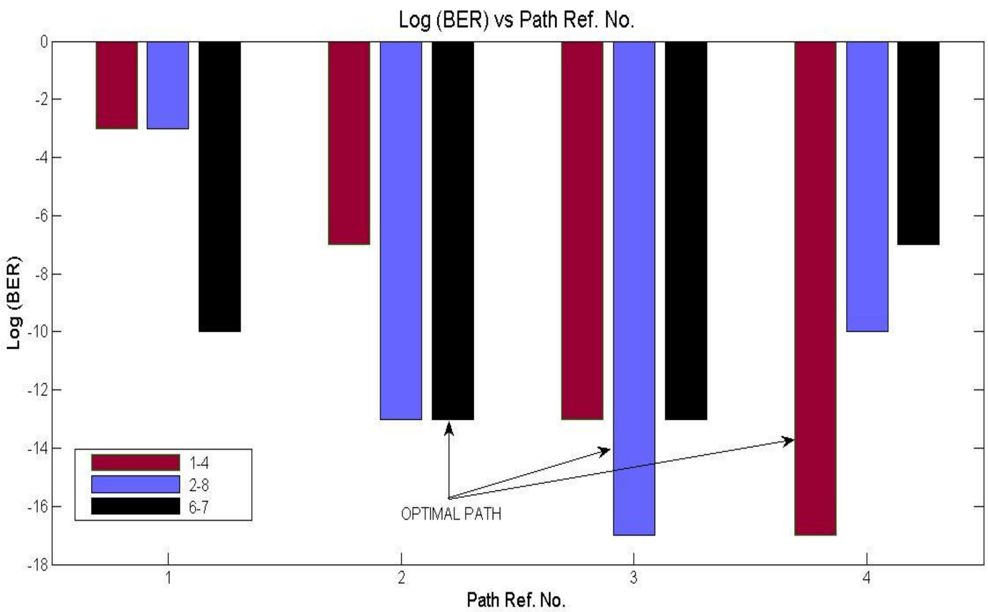

Fig. 4.8 log (BER) v/s path reference number showing optimal path selected by our algorithm

4.5 Simulation result for BER constrained based FWM aware algorithm

In this section we have simulated our second algorithm, where FWM is taken into consideration during the wavelength assignment phase. Simulations are done on the same topology and with the same parameter as given in the previous section. We have divided our 6 wavelength transmission window into two segments; an inner segment for shorter light path and an outer segment reserved for longer light paths respectively. Inner and outer segments are further divided into two segments. So entirely we have divided our transmission window into four segments.

The division of the transmission window is based upon an algorithm as given in [28]. Here we have calculated the threshold distance for the traffic matrix given in the previous section and the results are shown in the table 4.

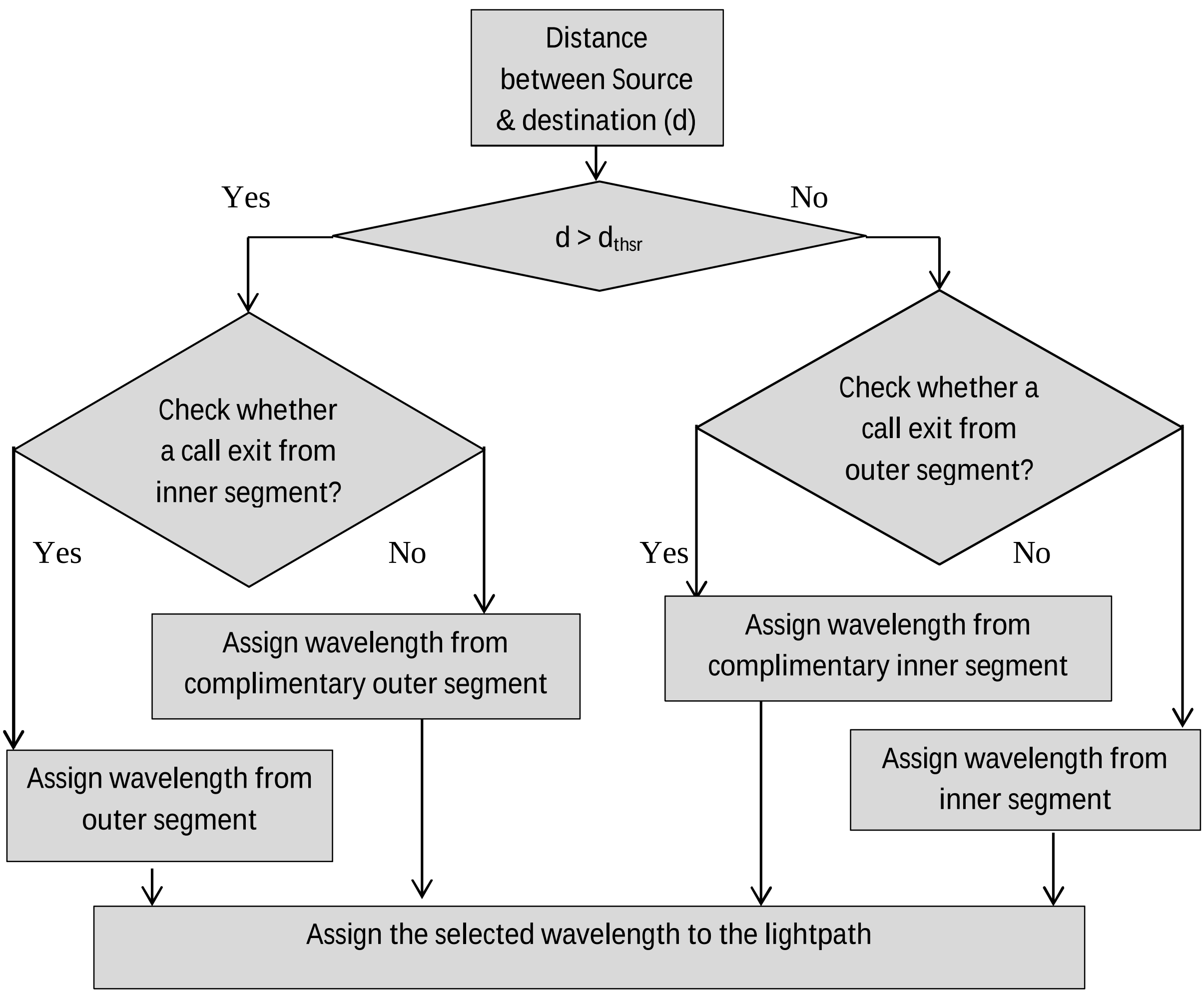

Fig. 4.9 Flowchart for FWM aware wavelength assignment technique

Source/Destination	Path	No of Connection	Distance in KM	Threshold distance (KM)
1-3	1-2-3	1	270	**171**
1-5	1-5	2	280	
1-6	1-6	1	120	
1-7	1-5-7	1	210	
2-1	2-1	2	300	
2-7	2-5-7	1	150	
2-8	2-5-7-8	1	200	
3-1	3-5-1	1	260	
3-6	3-5-6	2	380	
4-2	4-3-2	1	230	
4-8	4-8	1	120	
6-4	5-7-4	1	160	
6-1	6-1	1	120	
6-4	6-5-7-4	1	230	
8-7	8-7	1	50	

Table 4.3 Simulation result for threshold distance calculation in the process of FWM aware wavelength assignment techniques.

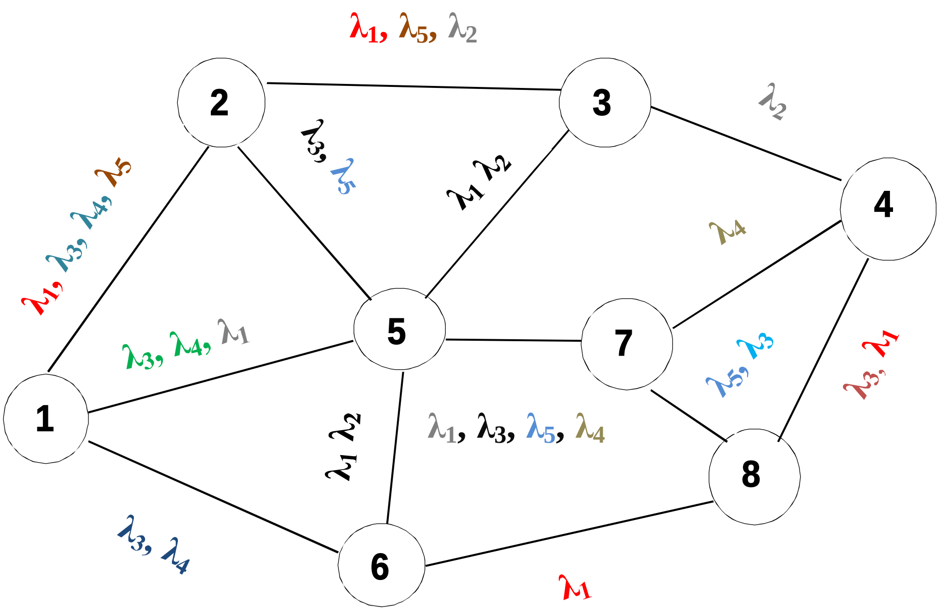

Fig.4.10 Network showing the existing connection using different colour for different wavelengths followed by FWM aware wavelength assignment scheme.

Source/ Destination	Possible Path	Path Ref. No	BER	Optimum Path
1-4	1-5-7-4	1	10^{-10}	1-5-3-4
	1-5-3-4	2	10^{-13}	
	1-2-3-4	3	10^{-13}	
	1-6-8-4	4	10^{-10}	
2-8	2-5-7-8	1	10^{-13}	2-5-6-8
	2-5-6-8	2	10^{-17}	
	2-3-4-8	3	10^{-17}	
	2-1-6-8	4	10^{-13}	
6-7	6-5-7	1	10^{-17}	6-5-7
	6-8-7	2	10^{-10}	
	6-8-4-7	3	10^{-10}	
	6-1-5-7	4	10^{-17}	

Table 4.4 Simulation result for optimal path selection

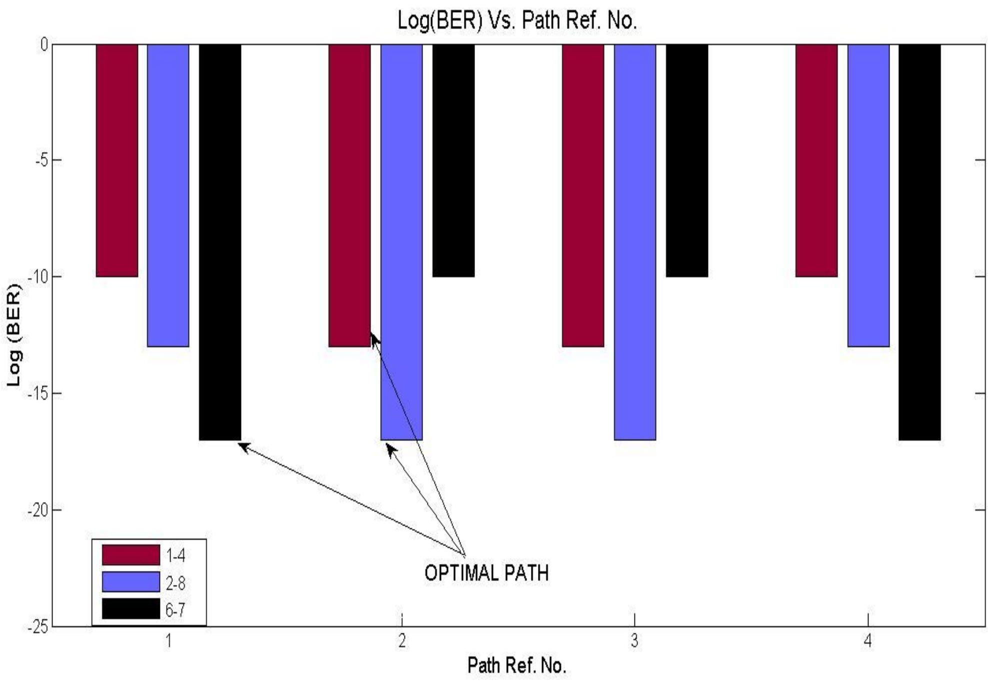

Fig. 4.11 log (BER) v/s path reference number showing optimal path selected by our algorithm

4.6 Comparison between the two wavelength assignment scheme

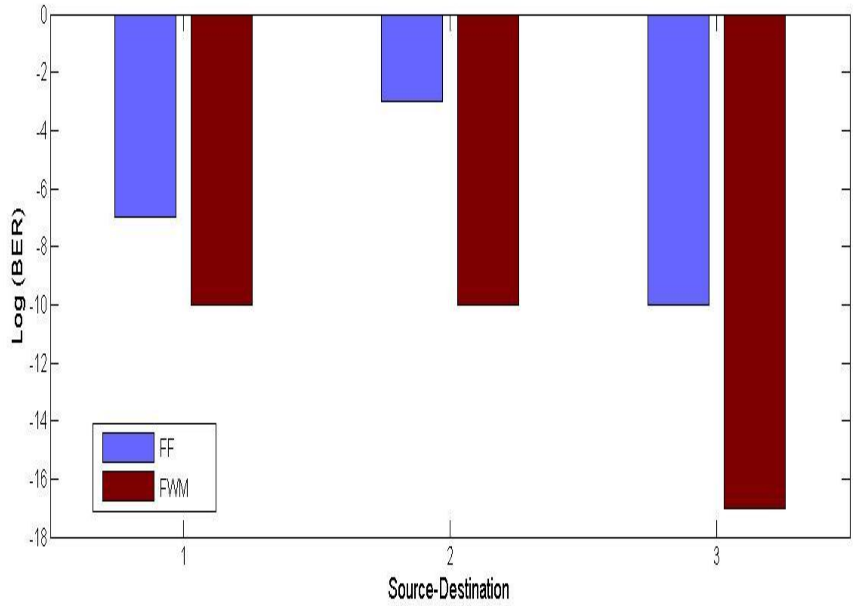

Fig. 4.12 log (BER) v/s path reference number showing optimal path selected by our algorithm

4.4 Blocking Probability

The simulation results show that BERC algorithm always select a connection with minimum BER. We compare our algorithm with traditional shortest path (TSP) and fixed alternate path routing (FAR) algorithm for overall network performance in terms of blocking probability. We have plotted blocking probability against number of connection to be established between randomly taken source and destination.

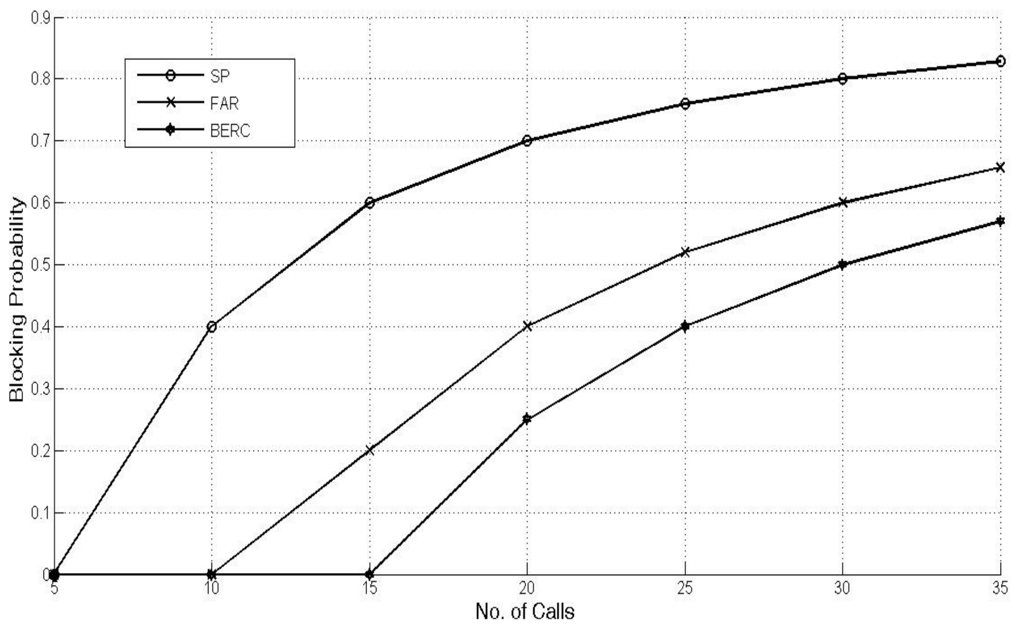

Fig. 4.13 Average call blocking probability for TSP, FAR and our BERC Algorithm

Result (in Fig. 4.7) show that BERC algorithm not only gives a guaranteed QoT but also reduces networks blocking probability. Another benefit of this algorithm is that it will distribute the entire traffic throughout the network so that a particular link will not be over loaded with the maximum number of traffic.

Chapter -5

Conclusion & Future Work

5.1 Conclusion

In this work, we have done a comprehensive survey on physical layer impairments and their impacts on transparent optical networks. Among the impairments we mainly focused on in-band crosstalk and try to incorporate its effect in the RWA algorithm. BER due to component crosstalk in a WDM receiver has been studied and computed results are shown by simulation as a function of number of interfering channel. A new algorithm is developed for efficient data path provisioning with guaranteed QoT in terms of BER. This algorithm is particularly very useful for high speed WDM/DWDM networks where, these impairments are high.

We compare our algorithm with algorithms that are not impairment aware and measured the network performance in terms of blocking probability. The result shows that our crosstalk aware algorithm reduces network blocking probability, utilizes network resources and give better quality of transmission as comparison to impairment unaware algorithms.

5.2 Future work

In future we will take other impairments into our consideration and impose latency constrain in the RWA process, which will further improve the network performance.

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Dissemination of my Work

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