CHAPTER-1

INTRODUCTION

1.1 Introduction to All-Optical WDM Networks

Wavelength routed all-optical networks are the class of backbone wide area networks (WANs) where connections are routed by intermediate nodes in the optical domain without electronic conversion. This involves establishing a connection in all optical networks by selecting a wavelength and a route for the purpose of linking the source of the connection to the destination of the connection with the same wavelength available on all fiber links of the route (wavelength continuity constraint). A connection established in the above manner is called a lightpath. Each fiber optic link can support many lightpaths by allocating each lightpath a discrete wavelength through WDM technology. Therefore, the number of WDM wavelengths employed in a single fiber link determines the number of independently addressable lightpaths in the WDM network. This number may be sufficient to meet overall network bandwidth requirements but still be inadequate to support the large number of nodes of a wide area all-optical network. In such cases the probability for call blocking arises due to wavelength contention when two calls at the same wavelength are to be routed using the same network link. This problem was overcome by the introduction of wavelength converters (WCs) which relax the wavelength continuity constraint and help to admit more calls into the network. Thus, WCs increase the call connection probability in WDM optical networks. The wavelength routing networks consist of Optical cross connect (OXC) comprised of passive multiplexers, demultiplexers and switches. An OXC having wavelength conversion facilities is capable of switching data from an input port on one wavelength to an output port on another wavelength. When such an OXC node is capable of converting a wavelength to any other wavelength, the node is said to have full conversion capability. When the node can convert an incoming wavelength to only a subset of available wavelengths at the node, it is said to have limited conversion capability and called L-WIXC (Limited Wavelength Interchanging Cross Connect) node. Since wavelength converter with full conversion capability is very expensive, all network nodes cannot be equipped with full conversion capability. WDM network with L-WIXC nodes employ optical amplifiers to compensate for the signal power loss introduced by the optical fibers and components. The L-WIXC and EDFA (Erbium Doped Fiber Amplifier) may cause significant transmission impairments such as crosstalk generation when two or more optical signals propagate through the same optical space switches of the nodes and generation of amplified spontaneous emission (ASE) noise by EDFA while providing signal amplification. This thesis considers the in-band crosstalk introduced by optical cross connect nodes and the ASE noise introduced by the EDFAs during the establishment of a light-path in a multi-hop WDM network.

1.2 Wavelength Division Multiplexing (WDM)

Theoretically, a silica fiber has enormous bandwidth which allows nearly 50 Tbps of bit rate potentially. It is about four orders of magnitude higher than the currently achievable electronic processing speed of tens of Gbps. Due to the limit of the electronic processing speed, the available bandwidth of the optical fiber cannot be fully utilized for transmission. Therefore, implementation of effective multiplexing technology like WDM is used to efficiently exploit the huge bandwidth capacity of the optical fibers. With WDM technology, we divide the large spectrum of the fiber in the low attenuation and low dispersion bands of 1550 and 1310 nm respectively into smaller orthogonal channels of fixed spacing and separation. This can be seen from Fig 1.1, which portrays the attenuation of light in a silica fiber as a function of wavelength. The curve shows that the two low-loss regions of a single-mode fiber extend over the wavelengths ranging from about 1270 to 1350 nm (the 1310-nm window) and from 1480 to 1600 nm (the 1550-nm window).

These regions can be viewed either in terms of spectral width (the wavelength band occupied by the light signal and its guard band) or by means of optical bandwidth (the frequency band occupied by the light signal). We can find the optical bandwidth corresponding to a particular spectral width in these regions using the fundamental relationship $c = v\lambda$ which relates the wavelength λ to the carrier frequency v, where c is the speed of light. Differentiating this we get,

$$|\Delta v| = \frac{c}{\lambda^2}|\Delta\lambda| \tag{1.1}$$

where the deviation in frequency $|\Delta v|$ corresponds to the wavelength deviation $\Delta\lambda$ around λ. From Eq. 1.1, it is found that the optical bandwidth Δv is 14 THz for a usable spectral band $\Delta\lambda$ =80 nm in the 1310-nm window. Similarly, Δv is 15 THz for a usable spectral band $\Delta\lambda = 120$ nm in the 1550-nm window. This yields a total available fiber bandwidth of about 30 THz in the two low-loss windows.

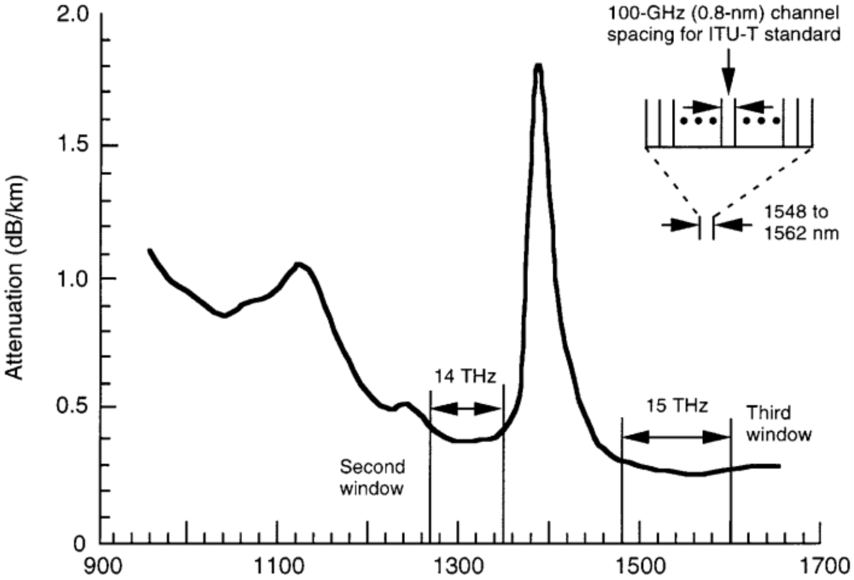

Fig 1.1 : Attenuation of Light in a Silica Fiber as a Function of Wavelength [28]

Since the spectral width of a high-quality source occupies only a narrow optical bandwidth, the two low-loss windows provide many operating regions. By using a number of light sources, each emitting at a different peak wavelength that is sufficiently spaced from its neighbor, the integrities of the independent messages from each source are maintained for subsequent conversion to electrical signals at the receiver. For example, if one takes a spectral band of 0.8 nm or, equivalently, a frequency band of 100 GHz within which a narrow-linewidth laser is transmitting, then one can send 50 independent signals in the 1530 to 1560-nm band on a single fiber which is the basic of WDM system.

The literature often uses the term dense WDM, which does not denote a precise operating region or implementation condition, it is a historically derived designation. Originally WDM was used to upgrade the capacity of installed point-to-point transmission links which was achieved by adding wavelengths separated by several tens or hundreds of nanometers. The purpose had been to keep the requirements on the different laser sources and the receiving optical wavelength splitters flexible. With the arrival of tunable lasers having extremely narrow linewidths in the late 1980s, very closely spaced signal bands became achievable. This was the origin of the term dense WDM or DWDM.

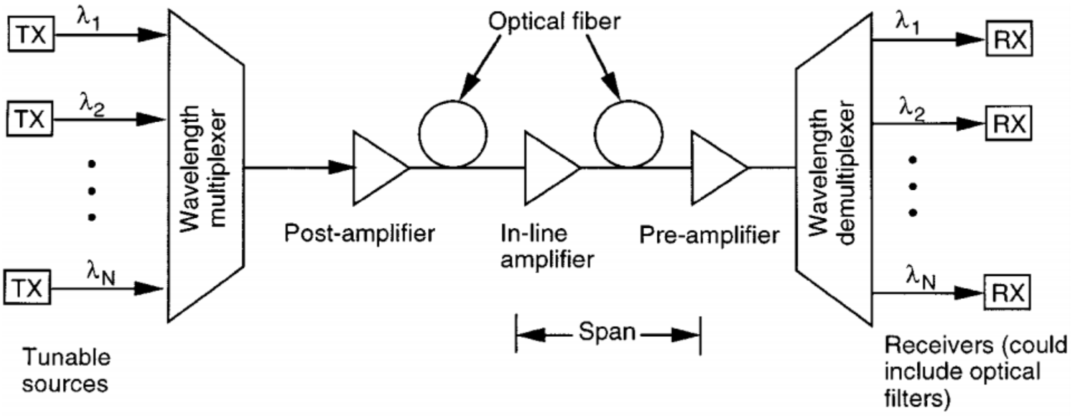

Figure 1.2 A typical point-to-point WDM link

Fig 1.2 shows a typical WDM link with several independently modulated light sources which are emitting signal at a unique wavelength at the transmitting end. A multiplexer combines these optical outputs into a continuous spectrum of signals and couples them onto a single fiber. At the receiving end a demultiplexer is used to separate the optical signals into appropriate detection channels.

1.3 The Advantages of WDM Network

The historical trends have been to increase capacity in the network and at the same time drive down the cost per bit of bandwidth. There are fundamentally three ways of increasing transmission capacity:

a. The first approach is to light up additional fibers or to deploy additional fibers as needed. This is called space division multiplexing (SDM) in which keep the bit rate same but use more fiber.

b. Multiplexing more than one signal on time slot basis that is called Time division multiplexing (TDM).

c. Adding additional wavelengths over the same fiber which is called Wavelength division multiplexing (WDM).

SDM is a straightforward upgrade alternative. It is expensive and time consuming. It becomes difficult if fiber has to be deployed in dense metropolitan area. TDM is useful for grooming traffic at the lower bit rate where optics is not cost effective. At the higher bit rate we have to deal with more transmission impairments over the fiber, specifically chromatic dispersion, polarization- mode dispersion and fiber nonlinearity. In standard single-mode fiber the chromatic dispersion limit is about 60 Km at 10 Gb/s and about 1000 Km at 2.5 Gb/s assuming transmission around 1550 nm. With practical transmitters the distances are even smaller. The 10 Gb/s limit may be further reduced in the presence of self-phase modulation. Beyond these distances the signal must be electronically regenerated or some form of chromatic dispersion compensation must be employed. Finally, nonlinearity effects such as self phase modulation(SPM) limit the maximum transmission power per channel, resulting in a need for closer amplifier spacing which leads somewhat higher cost. It is also difficult to be implemented since it needs ultra-short optical pulse sources and ultra high speed synchronization systems. WDM allows to maintain a modest transmission bit rate and have multiple wavelengths over a single fiber. Keeping bit rate low makes the system less vulnerable to chromatic dispersion, polarization-mode dispersion and some types of nonlinearities such as self-phase modulation. On the other hand it is not suitable for deployment over dispersion-shifted fiber because of limitation imposed by FWM. WDM allows different wavelengths to carry data at different bit rates and protocol formats which can be a major advantage in some cases. It provides the increase of the transmission capacity of existing fiber links smoothly without reaching the physical limits imposed by current optical technologies. Finally WDM provide flexibility in building networks. It devotes cost effective facility to dynamic and flexible rerouting and path protection which is more important when the total and link by link traffic load of the network either increases or decreases.

1.4 Motivation of the Thesis

Limited-wavelength-interchanging cross connect (L-WIXC) architectures is very promising for Wavelength Division Multiplexing (WDM) network as they can ensure the optimum use of limited resources and improves the BER performance and power penalty [1]. The use of wavelength converters in an Optical Cross Connect (OXC) ensures optimum performance and minimum expense through efficient design considering their cost and complexity. Several OXC architectures have been proposed in [1-3] with and without wavelength conversion capability. The key components required to implement an OXC node are passive multiplexers, demultiplexers, splitters, combiners and switches. Propagation through the switching elements that are part of the OXC results in signal degradation both due to device intrinsic losses and their imperfect operation and induces crosstalk. Despite the enormous promises of WDM for optical networking, crosstalk has remained as a major limitation of the practical implementation of OXCs. The network performance will be limited due to the coherent and incoherent crosstalk which gives rise to a significant signal degradation and power penalty leading to an increased bit error probability [8-9]. Practical implementation of the OXCs often employs multi-stage structures to achieve the required size with less complexity. The architectures of the optical cross-connects have a significant impact on how the unwanted light leaking from the components mix with the actual signal to become crosstalk. In [3] a systematic analysis of such crosstalk has been reported for different architecture of L-WIXCs considering individual optical components to find out overall crosstalk to enable system architects for achieving a desired crosstalk performance by choosing particular OXC architecture.

In a practical WDM optical network, signal is attenuated by the fiber and optical components, such as multiplexers and demultiplexers, splitters and couplers, tap, optical switches as they propagate through it. Moreover, in a long-haul communication system the cumulative loss of signal strength has to be restored using optical amplifier. All amplifiers degrade the signal to noise (SNR) of the amplified signal because of spontaneous emission that adds noise to the signal during its amplification [9]. Such performance limitations due to noise induced by optical amplifiers along with shot noise, thermal noise and crosstalk induced noise in bidirectional WDM ring networks has been analyzed [24]. A novel optical metro node architecture with monolithically integrated WDM optical cross connects based on semiconductor optical amplifier (SOA) is presented in [25-27]. It has been found that splitting loss caused by broadcasting stages can be compensated by amplifiers but noise added by SOA leads to optical signal to noise ratio (OSNR) degradation [9-11]. However, while the effect of crosstalk in WDM network design was previously studied and partially estimated, no or a little effort can be tracked on the performance of WDM network in the presence of L-WIXC and optical amplifier considering its impact on transmission performance. Therefore, in this research, the WDM network performance with various L-WIXC architecture is investigated considering that the signal traverse multiple hops taking into account the combined effect of noise and crosstalk.

1.5 Review of Previous Research Works

A lot of research works have been done on Optical cross-connect, their architectures, different type of crosstalk involved while propagating a signal through it and their type and impact. Some are given bellow.

The impact of coherent and incoherent crosstalk on an optical signal passing through the optical cross-connect nodes networks is shown in [1]. The analytical expressions are given are given and he statistical impact of all crosstalk contributions on signal is studied by simulation and the crosstalk specification requirements are obtained for components used in WDM optical networks with different scales.

In [2], T.Y Chai et al (2002) addresses the architectures that may be used to provide wavelength conversion in an optical cross-connect node where the converters may be shared either in a share- per-link or share-per node basis. Different ways of implementing OXCs with converter sharing using space- switching matrices, delivery-and-coupling switches and various combinations of couplers and filters have been presented and compared in terms of various features like complexity, expandability, upgradability, degree of wavelength converter sharing and blocking probability performance under different traffic loading.

Inband crosstalk in several important classes of optical cross-connect (OXC) architectures is presented the expression for the power penalty imposed by crosstalk is derived to compare the architectures in a systematic way in [3]. This in turn, enabled to study the relation between crosstalk and the component requirement.

In [5], an analytical approach for modeling crosstalk is presented and the impact of different factors of OXC on the performance of a WDM transmission link is also investigated with wavelength converter. Factors affecting the magnitude of crosstalk in the OXC are investigated and identified. The effects of OXC induced crosstalk on the BER performance is evaluated at a bit rate of 10 Gbps and the results show that for optimized values of gate extinction ratio, filter transmission factor, and number of wavelengths and input fibers, the minimum input power is approximately −10 to −8 dBm to maintain a BER of 10^{-9}.

In [9], the statistical impact of Coherent and Incoherent Crosstalk Contributions on the performance of a proposed single stage and a multi-stage Share-per-Node L-WIXC configuration and a multi-stage Share-per-Wavelength L-WIXC configuration is presented in terms of different Optical Propagation Delay Differences, Bit Duration etc. which is compared both theoretically and analytically. Considering Coherent and Incoherent Crosstalk contributions for each of those cases, analytical expressions of Electric Field, Leakage Crosstalk, Bit-Error-Rate (*BER*) and Power Penalty (*pp*) have been developed. The results obtained numerically, are thoroughly compared on the basis of Optimum Number of Wavelength Converters, Number of Inputs and Number of Wavelengths per Input Channel.

The effect of optical amplifiers in the presence of intraband crosstalk aroused in FBG-OC based BOXCs for bidirectional WDM ring networks (BWRN) has been investigated in [24]. Theoretical analysis is carried out to evaluate the performance limitations due to amplified spontaneous emission (ASE) of optical amplifier in a BWRN. BER and PP due to intraband crosstalk and ASE noise have been evaluated. It is found that Receiver sensitivity is significantly degraded which causes additional BER and power penalty due to signal-ASE beat noise induced in optical amplifiers. For long transmission distances through many optical amplifiers, signal amplified spontaneous emission (ASE) beat noise is dominating not only over the thermal receiver noise but also over the other receiver noise sources too. Such performance limitations due to ASE of optical amplifiers along with shot noise, thermal noise and crosstalk induced noise in bidirectional WDM ring networks has been verified in this paper.

Recently, layered OXC structure consisting of intramode sub-OXCs and intermode switching bridges for SDM/WDM network has been widely discussed in [10]. It is found that, fully connected cross-connections (OXC) converting all spatial modes and wavelengths into one-dimensional switching ports and followed by huge switching array can provide nonblocking switching, but the hardware implementation is very complex and expensive. In this paper, a layered OXC structure consisting of intramode sub-OXCs and intermode switching bridges has been proposed. Then, a scattered-spectrum-scan intramode-first routing and spectrum allocation (SSS-IMF-RSA) scheme is designed, in which only a few discrete spectrum segments instead of the whole spectrum should be scanned for spectrum allocation. The switching will be performed preferentially for the wavelength dimension because of mature switching capability and less searching time. It shows by simulation that the proposed layered OXC with the SSS-IMF-RSA scheme can achieve similar blocking performance to fully connected OXCs with up to 76.1% hardware scale reduction and 93% searching time reduction for network accommodation. The proposed OXC and RSA scheme greatly decrease the requirements for the port number of WSS and enable components reuse to achieve smooth evolution.

In [27], a novel optical metro node architecture that exploits the Wavelength Division Multiplexing (WDM) optical cross-connect nodes for interconnecting network elements, as well as computing and storage resources is discussed. The photonic WDM cross-connect node based on semiconductor optical amplifiers (SOA) allows switching data signals in wavelength, space, and time for fully exploiting statistical multiplexing. The advantages of using an SOA to realize the WDM cross-connect switch in terms of transparency, switching speed, photonic integrated amplification for loss-less operation, and gain equalization are verified experimentally. Moreover, the operation of the cross-connect switch with multiple WDM channels and diverse modulation formats is also investigated and reported. It has been found that splitting loss caused by broadcasting stages can be compensated by SOA but noise added by the SOA leads to optical signal to noise ratio (OSNR) degradation. Error-free operation with less than a 2 dB power penalty for a single channel, as well as WDM input operation, has been measured for multiple 10/20/40 Gb/s NRZ-OOK, 20 Gb/s PAM4, and data-rate adaptive DMT traffic. Compensation of the losses indicates that the modular architecture could scale to a larger number of ports.

1.6 Objectives of the Thesis

The main objectives of the research work are:

a. To develop an analytical model for a WDM multi-hop network considering the **combined effect of crosstalk and noise** due to different L-WIXC architectures and network components

b. To develop analytical expression for Signal to Crosstalk plus Noise ratio and BER considering different number of hops and different L-WIXC architectures in a multi-hop WDM network

c. To evaluate the BER performance of a multi-hop WDM network depending on number of hops, number of wavelengths and number of fibers for a given set of parameters

d. To determine optimum system parameters in terms of maximum allowable number of hops depending on specific power penalty level while maintaining a BER level of 10^{-9}

1.7 Organization of the Thesis

As mentioned in the title, the key objective of this work is to evaluate the performance of a multi-hop WDM network with L-WIXC architectures. The thesis has been organized as follows:

Chapter-2 presents a model multi-hop WDM network used for the analysis of the effects. Six different types of architectures of L-WIXCs are also presented for the evaluation of crosstalk contributions by the system components. Lastly, the role of EDFA in the said network is described.

Theoretical approach for analysis of crosstalk in six different types of L-WIXC architectures is provided in **Chapter-3**. An analytical model for the analysis of noise generated in a multi-hop WDM network is presented and the mathematical formulation for the combined effect of noise and crosstalk has been developed. From the said formulation, the expression for BER performance and Power Penalty performance has been presented which are simulated in the next chapter.

Chapter-4 studies the combined effect of noise generated by optical amplifiers and crosstalk contribution by L-WIXC architectures on the BER performance in a multi-hop network. Analyzing the BER performance for various system parameters i.e. number of hops, number of wavelengths and number of input fibers, the power penalty (PP) performance trend has been evaluated. Lastly, from the PP trends, maximum allowable number of hops for specific number of wavelength channels and number of input fibers in multi-hop WDM network has been presented and analyzed.

Chapter-5 concludes the thesis, summarizing the achievements of the research and provides scope of future works.