ABSTRACT

CHANDRASEKAR, KARTHIK. Optical Hardware Tradeoffs for All Optical Multicast. (Under the direction of Dr. Paul D. Franzon)

All Optical WDM Networks are fast becoming the natural choice for future backbones and in order to meet the exponentially increasing traffic demands, it would be beneficial to support all optical multicast. One way to support multicast is to provide optical splitters at various switching nodes along the network. The main contribution of this thesis is in demonstrating that all optical multicast can be made practical for both 1:2 splitters and 1:N splitters through the proper incorporation of in-line EDFA's and other optical hardware components available off the shelf. Using electronics for 3-R regeneration at the intermediate nodes is costly and hence our model uses EDFA's. Most previous work in this direction has addressed multicast feasibility from an architectural standpoint while this thesis discusses issues from a physical designer's perspective. An All Optical CAD simulation tool from Virtual Photonics was used to simulate a variety of multicast networks taking into account relevant Nonlinear effects such as chromatic dispersion, four wave mixing, stimulated Raman scattering and all phenomena commonly encountered in Cascaded EDFA chains such as Accumulated Spontaneous emission noise, SNR Transients and Gain Saturation.

Optical Hardware Tradeoffs for All Optical Multicast

by

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Dr.Paul D. Franzon, Chairman of Advisory Committee

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Biography

Karthik Chandrsaekar was born in Chennai, India in 1978. He graduated from Sri Venkateswara College of Engineering, University of Madras with a Bachelor's degree in Electrical and Electronics Engineering. He worked as a student researcher at the Computer Aided Design Lab and the Supercomputer education research center at the Indian Institute of Science at Bangalore between Nov1999-Jan1999 and May2000-July2000 respectively. He joined the Master's program in North Carolina State University in August 2000 and worked on his MS thesis under the guidance of Dr.Paul Franzon. He is currently heading towards his doctoral degree and he works on dealing with On chip Inductance Issues in Deep Submicron IC design.

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Chapter 1

Introduction

1.1 Motivation and Contributions

Light can be sent long distances through high quality fiber with little dispersion or attenuation. The 1.5um wavelength that is commonly used in communication systems corresponds to a frequency of $2*10^{14}$ Hz. A bandwidth of even 0.1% of this carrier, 100GHz, is wider than any encountered in electrical systems. Optical systems are also much less susceptible to interference in comparison to electrical systems. A combination of the above factors has made optical communications the method of choice for distances over 100m.

With the proliferation of the Internet and the exponential growth in bandwidth demand, Wavelength Division Multiplexed (WDM) all optical transmission systems are fast becoming an attractive choice for future telecommunication applications. The WDM approach is to keep the bit rate the same and add more wavelengths, each carrying data at this bit rate. WDM is the most practical option today in comparison to the Space Division Multiplexing (SDM) and the Time Division Multiplexing (TDM) approaches. The SDM approach requires more fibers and a separate set of optical amplifiers for each fiber, which in turn contributes to a significant expense over long distances. Optical modules of very high frequency are needed in TDM to obtain speed increase in individual channels. The distance limit due to chromatic dispersion and Polarization mode dispersion is much larger for WDM transmission systems than for equivalent TDM systems due to lower bit rates per channel employed in the WDM approach. WDM systems are also more modular and cost effective compared to TDM in designing more complicated networks and they are the preferred choice in this thesis. A more detailed discussion of the tradeoffs can be found in [1].

Most commercial fiber optic networks today deploy electronic switching or electro-optical switching. In order to obtain very high speeds it is essential for the signal to remain photonic throughout its path (i.e. all optical). All Optical Networks consist of Optical Fiber links between nodes with all optical switching and routing of signals at the nodes without electronic regeneration All Optical WDM Networks are very much a reality in the not too distant future with the advent of Erbium Doped Fiber Amplifiers (EDFA's), Raman amplifiers, optical crossconnects, Non Zero Dispersion compensating fibers and other state of the art optical devices. The advantages offered by these systems in the telecommunication industry are compelling. All Optical WDM networks offer transparency to bit rates, protocol formats and they also eliminate the need for costly electronic 3R regeneration at the intermediate nodes. All optical networks may form the national backbone in the not too distant future and even in the access network we may see all optical solutions for metropoliton area networks. Fig 1 below depicts a block diagram for a typical 4 channel All Optical WDM transmission system.

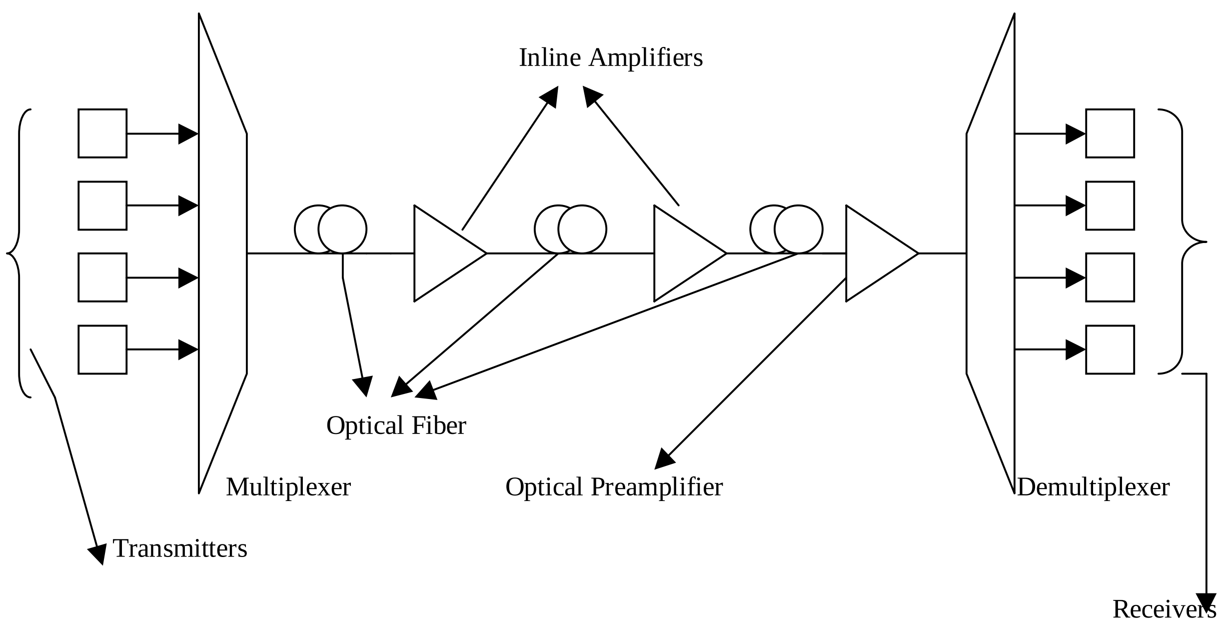

Fig 1: A Typical All Optical WDM transmission system

In order to meet the exponentially increasing traffic demands of the Internet it would be beneficial to support all optical multicast. Multicasting can reduce both the bandwidth consumed and the number of wavelengths required if the size of each multicasting session is reasonably large [2]. Examples of Multicast Applications include video teleconferencing and audio/video broadcast over the Internet. This thesis aims at the design and simulation of an All Optical Multicast System. In order to provide multicast support the signal needs to be split at various switching nodes along the network. One way to support all optical multicast is to provide optical splitters at various switching nodes along the network. An Optical Splitter splits the input signal into multiple identical output signals. Since an optical splitter is a passive device the power of each output signal is 1/n times the input signal. In addition to various losses typically encountered in a fiber optic communication system there is loss due to signal splitting too. To be detected the signal needs to be more than a threshold value and hence a network with multicast capable switches would require more number of optical amplifiers, which in turn would increase the Accumulated Spontaneous Emission Noise (ASE).

The main contribution of this thesis is in demonstrating that all optical multicast can be made practical for both 1:2 and 1:n splitters through the proper incorporation of inline EDFA's and other optical hardware components available off the shelf. This offers great potential for cost effective implementation in Short Haul and Medium Haul systems. A wide variety of all optical multicast systems are simulated using a commercial all optical CAD simulation tool from Virtual Photonics and the thesis provides results documenting the number of splits that can be supported for various fiber optic link lengths as a function of the number of EDFA's. It also provides results and insight into various effects typically encountered in Cascaded EDFA chains, system scalability issues such as supporting a greater number of wavelength channels, higher bit rates and potential for implementation of all optical multicast in long haul systems. The results obtained from the CAD simulation tool are accurate to 3-sigma confidence levels and it takes into account effects such as chromatic dispersion, polarization mode dispersion and fiber non-linearities such as four wave mixing and Stimulated Raman Scattering.

1.2 Thesis Organization

Chapter 2 starts off with a review of recent work in Modelling Optically Amplified WDM transmission systems and Noise analysis in Cascaded EDFA chains. The latter half of the chapter reviews the current state of the art in All Optical Multicast systems with an emphasis on Optical splitter technologies, Optical crossconnect architectures and Optimum Optical Amplifier Placement schemes to meet the system needs.

Chapter 3 discusses tradeoffs involved in choosing from a wide variety of Optical Hardware components for designing the All Optical Multicast system. In particular it discusses the choice of fiber, transmitter and receiver, optical filters, Optical add/drop multiplexers and the limitations placed by chromatic dispersion and polarization mode dispersion on high bit rate long haul systems. It also supports the arguments made with a few simulation results. The latter half of the chapter focuses on optimum optical amplifier placement and its impact on ASE noise and Signal to Noise Ratio.

Chapter 4 treats the design and modeling of All Optical Multicast Systems. It builds on ideas and thoughts presented in chapter3. The design flow is clearly highlighted and it introduces the idea of multicast capable switching nodes and also discusses the chosen Network Architecture. Justification is provided for choice of the all-optical multicast systems chosen for the study. A slightly modified optical amplifier placement scheme is suggested for all optical multicast systems. SNR and Power transients in cascaded EDFA chains in the presence of a single channel discontinuity and Gain transients in the presence of optical bursts are studied. The choice of parameter values in the simulation model for all optical multicast systems is highlighted and this is accompanied with a mention of how the simulation tool takes into account the effect of dispersion, non-linearities and noise. Results obtained from this analysis are presented towards the end of the chapter along with a brief interpretation of the results. Results include the Number of splits that can be supported for link lengths of 600 Km and 1000 Km as a function of the number of EDFA’s used and

Eye diagrams obtained at the receiver end for these systems. The chapter concludes with a brief discussion of scalability issues.

Chapter 5 summarizes the conclusions drawn on the basis of the results obtained. Suggestions for future work are also presented.

Chapter 2: Background and Literature Review

2.1 Modelling Optically Amplified WDM Transmission Systems

Hand analysis procedures for studying optically amplified WDM transmission systems are rather cumbersome due to the large number of physical effeccts to take into account and also because of the complex interdependence between the various physical effects. With the advent of WDM and passive split amplifiers, simple back of the hand calculations no longer serve their purpose. The effects of amplifier noise and wavelength response, optical crosstalk, chromatic dispersion, non-linear effects such as four wave mixing and stimulated Raman scattering all need to be considered simultaneously for efficient design of high bit rate Light wave systems. A brief overview of the current and future trends in the CAD simulation of all Optical systems is briefed upon in this section.

It has been only recently that integrated computer aided design tools for All Optical systems have been made available commercially. Most of the early CAD tools were either power budget based or were designed for Bit Error Rate (BER) prediction in Long Haul Systems [3]. For detailed BER prediction the usual simulation method involves the sampling and transmission of a complex signal waveform through the system, using Fourier Transform techniques [4]. This method takes a lot of simulation time and in order to overcome this drawback each signal on the network is transmitted separately and only combined with the others if necessary. This ensures that wideband ASE noise and multiple signals can be handled efficiently without the need to time sample at the nyquist frequency of the combined multiplex. Over the years CAD tools have evolved which combine both Power budget and BER estimation and also take much less time due to simplified accurate component models coupled with improved signal processing techniques.

Some of the popular tools include VPI WDM transmission maker from Virtual Photonics Incorporated Systems, OPALS (Optoelectronic, Photonic and Advanced Laser Simulator) from the Photonics Research

Laboratory at the University of Melbourne and LinkSim (Optical Link Simulation package) from Rsoft research Software [5]. Companies such as British Telecom Labs and France Telecom Institute are pioneers in developing there own in house all optical cad tools to design transmission systems from the component level to the network level. Tools are also available which simulate and optimize performance of specific components in the WDM transmission system such as Optical Amplifiers. For example OASIX is a user friendly erbium-doped fiber amplifier package developed by Lucent technologies capable of accurately predicting the perfomance of erbium – doped fibers when used as single-stage amplifiers, dual stage amplifiers or ASE sources and can also simulate EDFA designs with a host of optical components such as filters, isolators and reflectors.

2.2 Cascaded EDFA chains

A combination of several factors has made the EDFA the amplifier of choice in today's optical communication systems. This includes the availability of compact and reliable high-power semiconductor pump lasers, the fact that it is an all fiber device making it polarization independent and easy to couple light in and out, the simplicity of the device and the fact that it introduces no crosstalk when amplifying WDM signals. EDFA's can also be manufactured with a twenty-five year reliability that is required for use in undersea systems. The simplest way to analyze a cascade of optical amplifiers is to assume that all amplifiers have the same gain and that the loss between amplifiers exactly matches the amplifier gain. The design of the amplifier chains must provide control of the optical power level, must address control of noise accumulation, must provide an adequate optical bandwidth for the data channels, and must minimize pulse distortion caused by chromatic dispersion and nonlinear effects.

An undesirable effect of using optical amplifiers is that they introduce spontaneous emission noise. For distances larger than 500km the accumulated spontaneous emission (ASE) noise generated in the EDFA's can accumulate to power levels similar to the data-carrying signal, which in turn degrades the signal to noise ratio of the system. So in addition to suitably amplifying the signal to satisfy the receiver's sensitivity constraints one also has to be concerned about the signal to noise ratio at the receiver which might deteriorate particularly in systems having a large number of cascaded amplifiers. The interesting tradeoffs between output SNR and amplifier placement are central to designing all optical multicast systems. A brief discussion regarding this can be found in [6] which suggest that longer systems require shorter amplifier spacings to keep the same output SNR. However typical route design imperatives and economics dictate that the total number of optical amplifiers used along the link be minimized [1]. A comprehensive guide to choosing the right optical amplifier placement scheme for an Optical LAN/MAN based on passive star couplers and WDM can be found in [7] and a more general approach is given in [1]. Both the approaches aim at minimizing the number of optical amplifiers used along the network when all the wavelengths at a particular point in a fiber are equally powered and when they are unequally powered. Output SNR depends on both choosing the optimal optical amplifier placement scheme and optimum power levels in order to reduce non-linear effects. This idea is supported by results in [6] which indicates that the optimal number of optical amplifiers is limited more by the increasing non-linear effects with signal power rather than ASE noise.

In real world networks sizeable system impairments may result from channel addition or loss in a point-to-point communication link composed of a long chain of EDFA's. Hence it is important to study transient time behaviour for cascaded EDFA's to the gain or loss of one or more wavelength channels in a WDM circuit switched or packet switched scenario before determining the system's feasibility in the long run. Significant results in this direction are reported in [8] which conclude that substantial SNR and power swings are present when an EDFA is used to amplify highly variable burst- mode packet traffic and that this effect is more pronounced along a cascade with power swings in excess of 9 dBm and SNR swings in excess of 4 dB are observed. This could limit the receiver's dynamic range and also produce inadequate eye opening at the receiver. The end application for the all-optical multicast system proposed in this thesis is in Optical Burst switched networks. Methods for stabilizing the gain of EDFA's in Optical burst switched networks are listed in [9].

2.3 All Optical Multicast Systems

The advantages of WDM All Optical Multicast systems, although well known since the early 1990s, have not generated any serious deployment plans to date because the components are on later learning curves than those for conventional components and also the need for an upgradable high bandwidth system has not been adequately demonstrated. But now we are at a point where high capacity, upgradable architectures such as WDM PONs may become more of a necessity for greatly extended communications capacity in commerce, education and entertainment. Wagner, Lemberg and others pioneered the WDM PON idea as access architecture at Bellcore [10] .WDM in this context allows the Central Office to send multiplexed signals, each at a different wavelength to a Remote terminal. The remote terminal, in turn, contains a wavelength division demultiplexer that passively splits the light by wavelength, directing each color to an assigned subscriber effectively acting as a switch.

Most recent work in this direction has addressed multicast feasibility from an architectural standpoint while this thesis discusses issues from a physical designer's perspective. Benefits of All Optical Multicasting are addressed adequately in [2] and this further emphasizes the need for all optical multicast systems. The closest works in the context of this thesis are [11,12] which discuss the modeling of optically amplified splitter based networks for relatively short haul systems while this thesis addresses medium haul and long haul systems. A systematic procedure for developing an Optical simulation tool for studying Passive Optically Amplified networks (i.e optically amplified splitter based networks) is also reported in [13] and it served as a excellent starting point for this thesis.

In the following paragraphs All Optical Switches and Optical Splitter technologies are reviewed, as they are fundamental to enabling functionality of an All Optical Multicast System. All Optical Switches are the primary bottleneck in making all optical systems a reality and are only now beginning to be available off the shelf. Fig 2. Below depicts a block diagram for an Optical Crossconnect employing space switches and Wavelength Path routing. Competitors in the race for an effective optical switch have developed technologies that range from microscopic mirrors to miniature bubbles to liquid crystals. Early last year, for example, Lucent's Bell Labs built what it called "The world's first practical optical switching technology using MEMS." The device is based on a tiny pivoting bar with a gold-plated mirror at one end that fits in a tiny space between two hair-thin optical fibers lined up end to end [14]. Calient's Diamond Wave photonic switch utilizes a purely photonic datapath and will dynamically establish wavelength paths via a signaling protocol, it truly can be called a photonic switch opposed to an optical crossconnect. It has Seamless Scalability from 8 to 4096 ports per system, a low loss datapath, Industry's widest operating window (1200 - 1620nm) supporting single and multi-wavelength applications [15]. Agilent Technologies, Inc., a company spawned by Hewlett Packard, uses bubbles to shuffle light packets between tiny waveguides made of glass. Corning Inc. and Chorum Technologies Inc. rely on liquid crystals to shift light beams from one path to another. Nanovation Technologies, meanwhile, is developing a hybrid technology that integrates MEMS-based optical switches with silica-on-silicon waveguides on a single chip. ; OMM'S Three dimensional MEMS technology utilizes a proprietary scanning mirror design to realize photonic switching subsystems which enable communications equipment manufacturers to build large scale optical crossconnect switching systems. Each mirror is based on a proprietary double gimbaled design, which allows high-resolution switch path positioning from any input to any output. Because there is no electronic conversion of the optical signal OMM photonic switches accommodate any data rate and signal format to meet rapidly evolving network requirements [16].

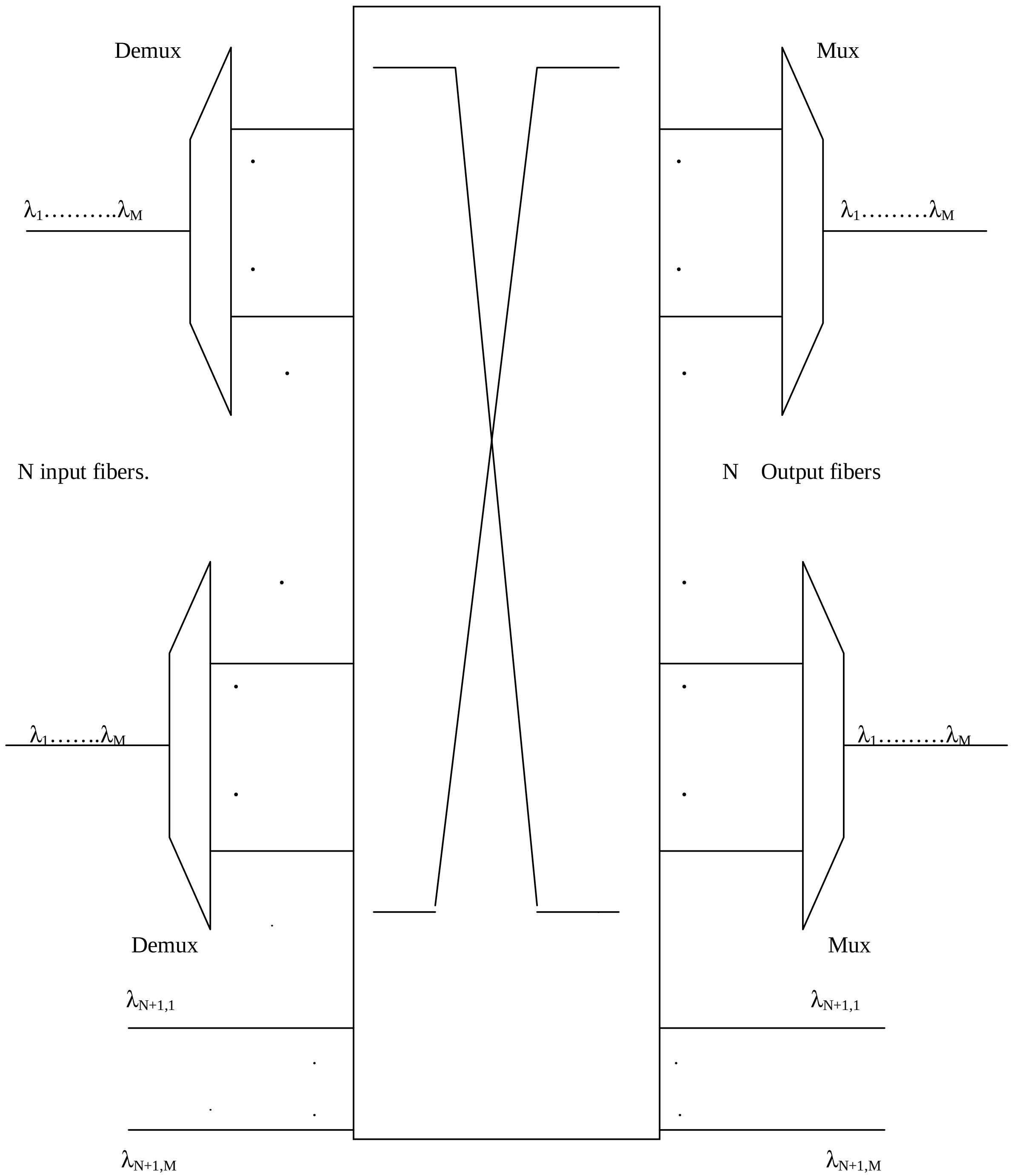

Fig 2: Optical Cross connect based on M (N+1) X M (N+1) Space Switch

Passive Optical Splitters eliminate active electronics in the local loop and they have enabled highly efficient point to multipoint passive optical networks. Passive Optical Networks offer significant advantages as optical fiber feeders because of their low deployment cost, low maintenance requirement and high bandwidth (WDM overlay). A 1:N optical power splitter divides input signal power between N output ports thus reducing the input signal power by a factor N called the splitting ratio. Splitters introduce power loss (due to power distribution and insertion loss). Fig 3 below shows a block diagram for a 1:4 Optical Power Splitter obtained from the CAD tool used in this effort.

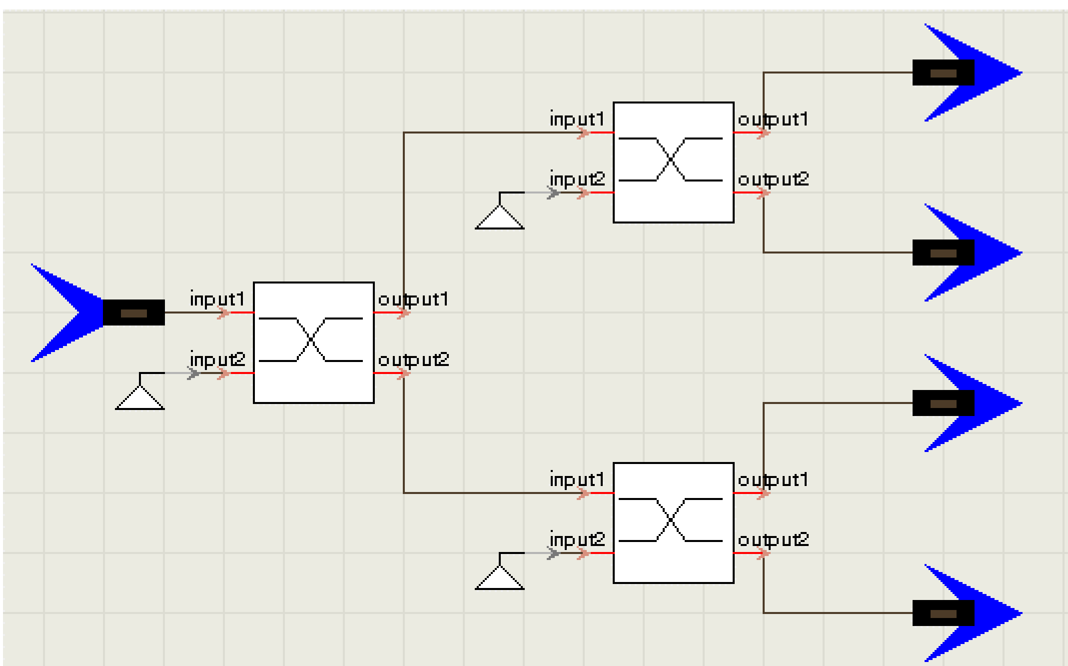

Fig 3 - 1: 4 Optical Power Splitter

Splitters are also fabricated on Si/SiO_2 platform for ease of coupling with optical fibers. Planar Lightwave Circuit Splitter modules are thoroughly investigated in [17] with reference to the Bellcore requirements. The reported module is composed of Y-branching silica based waveguides on Si connected to optical fiber with UV curable adhesives and is packaged in a metal case which is filled with humidity resistant resin. High optical performance such as low loss, low reflection and thermal stability are reported through the use of this fiber connection technique. 1:2,1:4 and 1:8 optical splitters are now available off the shelf and a few manufacturers also report generic 1:N optical splitters with N ranging anywhere between two to thirty two. For example Aurora Networks offer dual 2 way, 4 way and 8 way splitter/combiner modules with low insertion and polarization dependent loss using SC type connectors.

Chapter 3: All Optical Transmission Systems

3.1 Choice of Optical Hardware Components

Optical Transmitters/Receivers

The key system design parameters related to the transmitter are its output power, rise/fall time, extinction ratio, modulation type, side-mode suppression ratio and temperature /wavelength stability. The output power depends on the type of transmitter used. DFB Lasers put out about 1 mWatt to 10 mWatt (10 dBm) of power. Lasers tend to be physically limited by peak transmit power; however upper limits on output power are usually limited by eye safety regulations. Fiber non-linearities scale with the square of optical power output and this is a major design consideration too. The rise/fall time values must be as small as possible (limited by generation of high-frequency components) in order to increase the optical bandwidth. The laser at the transmitter may be modulated directly or a separate external modulator may be used. Direct modulation is cheaper but results in a broader spectral width due to chirp. This will result in an added power penalty due to chromatic dispersion. This penalty can be reduced by reducing the extinction ratio. Inexpensive low-speed optical communication systems use Light - emitting diodes for the transmitter. The major advantage of LED's is their low cost. However they have poor conversion efficiency, limited bandwidth and low optical power output. Thus LED transmitters would be more suited in optical links that operate at modest bit rates (< 100 Mbits/s) over short distances (up to a few kilometers). Laser Diodes have much better conversion efficiency in comparison to LED's and produce much higher output power (up to 1W or so). DFB Lasers are currently highly preferred in comparison to FP Lasers in long distance high-speed links because they have low levels of noise and a high side mode suppression ratio [1]. Typical temperature caused wavelength shifts are just under 0.1 nm per degree Celsius, which provides 3-5 times better performance than conventional laser diodes. Since the proposed application in this effort is essentially medium or long haul in nature DFB Lasers modulated by a Pseudo Random Bit Seuqnce (PRBS) are chosen. The transmitter is designed for operation in the range defined by the MONET wavelengths (1.5 mi-crometer band). An Average Power Control Loop is used to stabilize optical output power against temperature variations, which would potentially result in cost savings due to elimination of the TEC setup usually required for the Laser.

The key system parameters associated with a receiver are its sensitivity and its dynamic range. Avalanche photodiodes (APD) have excellent linearity over optic power levels ranging from a fraction of a nanowatt to several microwatts. If more than a microwatt is available at the receiver an APD is usually not needed. At this power level PIN diodes provide enough responsivity and sufficiently large signal to noise ratios. Silicon is the most practical fiber optic detector in the first window but it has low responsivity in the 1.5micro-meter band. InGaAs diodes introduce more noise than silicon but they are more responsive in the 1.5micro-meter wavelength band. A suitable tradeoff is made here. In APD's a large value of multiplicative gain is accompanied by a large variance in generated photocurrent, which adversely affects the noise performance of the APD. However they can be designed with optimum values chosen to achieve desired performance. Here the chosen configuration consists of an EDFA (serving as an optical preamplifier at the receiver end) followed by an APD detector. Higher sensitivity, Noise suppression and wider dynamic ranges are obtained by using an Optical pre-amplifier [18]. Values ranging between -20 dBm to -30 dBm are ideal values to have for the receiver sensitivity. In order to achieve transparency to bit rates and modulation formats it is essential that all the complexity of electronics be confined to the transmitter and the receiver ends. While there have been some attempts at Optical 3-R generation [19], it is an immature technology as yet and hence a suitable clock recovery circuit (typically a PLL) is employed at the receiver side to extract the bit clock and the data.

Optical Fiber

The choice of optical fiber is important in determining the dispersion-limited distance that a signal can travel without regeneration. The first fibers to be produced were multi-mode fibers having a core diameter of 62 um. Multi-mode fibers are structures with multiple pathways through which light travels. Within the core of these cables are several hundred layers of glass, each with a lower index of refraction as you move outward from the center. These fibers are still commonly used in local area networks because low cost light emitting diodes is readily launched into larger cores. For medium haul and long haul applications single mode fibers having a small core diameter of about 10um are preferred because of the higher bandwidth that they offer. In single mode fibers only one light wave at a time can be transmitted down the core. Because of quantum mechanical effects, the light traveling in the very narrow core stays together in packets, rather than bouncing around the core of the fiber. Single mode fiber designs remained unchanged throughout the 1980's when networks operated at 1.3 micro meter (um), the zero dispersion point of standard fiber. However current optical systems operate in the 1.5um window, as this is the lowest loss window for silica fibers and also due to the fact this is the region of operation for Erbium Doped Fiber Amplifiers. This brought about the development of Dispersion shifted Fibers, which had low loss and zero dispersion. Non-Linear effects such as four wave mixing and self phase modulation are a major deterrent in enabling high capacity WDM transmission systems. Non Zero Dispersion shifted fibers (NZDSF) were developed to reduce non-linear effects by introducing a controlled amount of dispersion. NZDSF has low attenuation in the EDFA C-band and some residual dispersion at 1550 nm. These NZDSF fibers along with Dispersion compensating Fibers (to keep system dispersion relatively low) are used in the All Optical Multicast System proposed in this thesis. The following two paragraphs present a few discussions for choosing NZDSF and DCF's over SMF based on simulation results obtained from an All Optical CAD simulation tool.

Chromatic dispersion is a key challenge limiting migration to next generation optical networks. Chromatic dispersion is the natural spreading of optical data pulses as they travel through the transport fiber (Figure 1). This pulse spreading occurs because the individual wavelengths that make up an optical pulse travel at slightly different speeds. Chromatic dispersion becomes a problem when the dispersed pulses begin to overlap and the network receiver can no longer distinguish the "ones" from the "zeros". The effect of chromatic dispersion is an intolerable increase in the bit error rate (BER), limiting the distance a signal can travel without regeneration. Fig 4 illustrates pictorially the concept of chromatic dispersion.

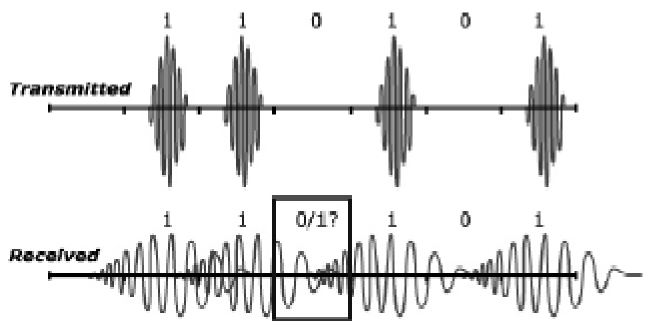

Fig 4: Chromatic Dispersion

Experiments were performed with three different optical link configurations to evaluate their suitability for medium haul and long haul applications. A single channel system was built over various lengths at different channel bit rates with EDFA's placed at 80 km spacings along the link. The transmit power of the channel was varied between 0 dBm to –5 dBm and the channel transmit wavelength is 1550 nm. The amplifiers were assumed to be noiseless in order to determine dispersion and non-linearity limited distances for optical links in isolation (of noise effects in cascaded EDFA's). The purpose of this study was to compare the performance of SMF, SMF+DCF and NZDSF+DCF and make a clear choice of one over the other in designing the All Optical Multicast System .Fig 5 depicts the experimental system that was simulated. A precompensation of Dprecomp = -170 ps/nm-Km was employed along with DCF's to prechirp the pulses and hence increase the transmission distance. Fig 6 summarizes the Fiber parameters used in the simulation.

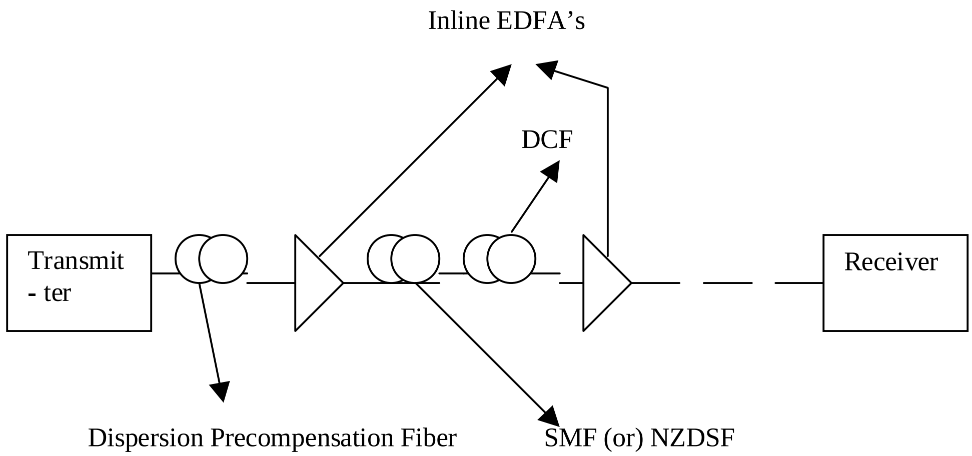

Fig 5: Experimental setup for comparing performance of optical links

	NZDSF	SMF	DCF
Dispersion (ps/nm-Km)	4	17	-290
Dispersion Slope (ps/nm^2-Km)	56	84	-84
Attenuation (dB/Km)	0.2	0.225	0.5
Non-Linearity coefficient (W^{-1}-Km^{-1})	1.9	1.4	5.8

Fig 6: Fiber Parameters used in the simulation

Results of this analysis are summarized in Fig 7. These results were arrived at by studying BER curves obtained at the receiver end as a figure of merit. Numerical values less than or equal to 10e-9 were assumed to be good for the bit error rate. These results clearly indicate that NZDSF fibers used along with suitably optimized length of DCF fibers would offer great potential for WDM systems. In this case the optimized lengths for the NZDSF and DCF fibers were found to be 69 km and 11 km respectively. However it is also important to note that the effects of Polarization mode dispersion and optical amplifier placement were ignored in this analysis, as the intent was to provide just a comparison. Both the above-mentioned factors are significant in enabling high bit rate long haul optical communications [20]. A brief discussion of polarization mode dispersion along with a few related simulation results are presented in the subsequent paragraph. Also a greater number of wavelength channels would be likely to cause increase in timing jitter due to non-linear effects such as cross phase modulation which occurs due to power of neighboring channels as well as neighboring pulses in same channel. A potential drawback with using NZDSF fibers is that they have a higher coefficient of non-linearity in comparison to SMF fibers and they have more dependence on the transmit power and the channel spacing.

	2.5Gbps	5Gbps	10Gbps
SMF	1800Km	480Km	115Km
SMF + DCF	2480Km	560Km	160Km
NZDSF+DCF	10,160Km	2480Km	640km

Fig 7: Dispersion and Non-Linearity Dependent Limited Distance for 3 Optical Links at 3 different bit rates

Polarization Mode Dispersion in Optical Fibers

Dependence of refractive index on wavelength leads to chromatic dispersion in single mode optical fibres. Similarly, in real optical fibres, the refractive index experienced by an optical signal will depend on the plane of polarization of the light in the fiber. This is termed *birefringence* and leads to polarization mode dispersion in fibres. Figure 12 shows the basic mechanism for the generation of polarization mode dispersion delay (PMD). At the transmitter end, the pulse is represented by the phasor sum of the x and y polarization components. As these components propagate through the fiber, the inherent birefringence causes one of the components to be delayed with respect to the other. In high bit rate systems, this differential group delay can lead to signal distortions and hence a degradation in the BER of the received signal. The group delay between two polarization components is called the differential group delay. Its average is the PMD delay (in ps) and is expressed by the PMD coefficient in ps/sqrt (km). The PMD does not increase linearly, but with the square root of transmission distance.

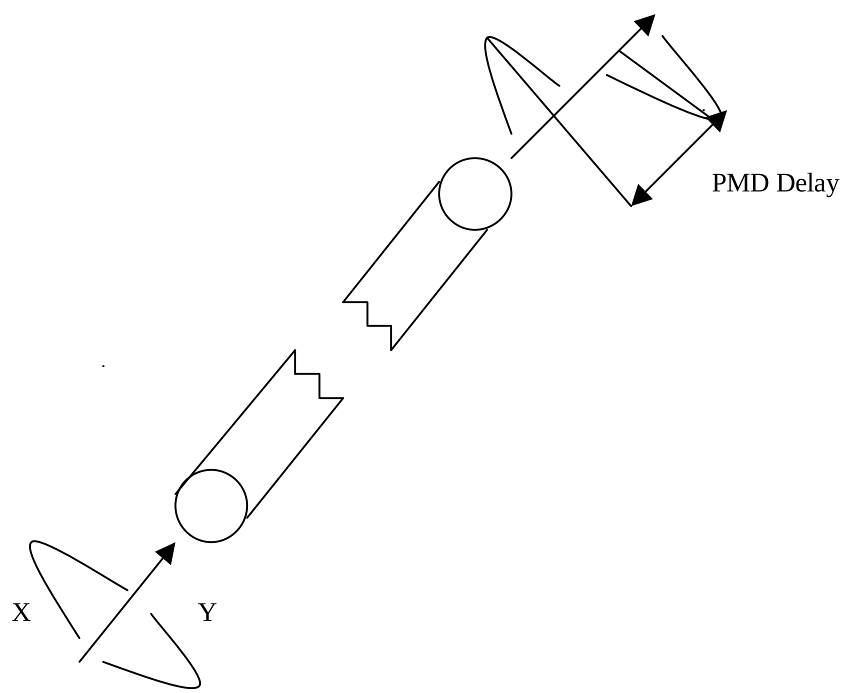

Fig 8: Group delay of two orthogonal (X & Y planes in the figure are orthogonal) polarizations after passing through a Single mode fiber

Simulations were performed on a fiber with typical PMD coefficient of 0.5 ps/sqrt (km) to determine the PMD limited distances for two different data transmission rates. The final choice of link lengths in the commercial deployment of All Optical Multicast systems should be influenced by PMD in addition to chromatic dispersion and non-linearities. Results of this analysis are presented in Fig 9. These results indicate that PMD is more of a series impediment at bit rates of 10Gbps and above. At these bit rates some form of PMD compensation would be required.

	2.5Gbps	10Gbps
0.5ps/sqrt (Km)	6400Km	400Km
0.3ps/sqrt (km)	16,000Km	1000Km
0.7ps/sqrt (Km)	3200Km	190Km

Fig 9: PMD Limited distances

Optical Filters:

In order that a WDM system be feasible for communication, there must exist a way to select channels which carry information specific to a given end-user. In particular, it is advantageous if such selection can be done in the optical domain as this offers numerous benefits. Optical filters offer various benefits such as low insertion loss, polarization insensitivity, stability with respect to environmental changes and little or no crosstalk [18]. Filters also perform the role of switches in optical systems, since one may select/ deselect a given signal via filters. Fabry-Perot filters are chosen in this effort to filter out noise and perform selection/deselection at the receiver end. This filter is based on the principle of a resonant cavity formed by two highly reflective mirrors placed parallel to each other [1]. The transmittance of a Fabry Perot filter is a periodic Lorentzian function of frequency. The transmittance function can be extremely narrow, depending on the design of the cavity. A parameter used to characterize such filters is the finesse, which is the ratio of the FSR (Free Spectral Range) and the bandwidth. These Filters typically have a finesse of around 100, with a bandwidth of 1nm or less and an insertion loss of 2 dB. Compact Fabry-Perot filters are commercially available components and their main advantage over some of the other devices is that they can be tuned to select different channels in a WDM system.

Optical Amplifiers

EDFA's are chosen due to reasons already discussed in chapter 2. It would be beyond the scope of this thesis to compare various amplification schemes, as the arguments in favor of EDFA's are compelling. Detailed discussions regarding this can be found in [21,18,1].

Optical Add/Drop Multiplexers

Optical Add/Drop multiplexers (OADM) can operate in the optical domain and hence a node comprised of OADM's cans add/drop an optical channel which is independent to data rates, protocol and signal formats used. OADM's provide flexible allocation of wavelengths network wide and this makes scalability easy to achieve. OADM's enable carriers to reconfigure network traffic in order to optimize data transport and obtain fast restoration in the event of network failure within the optical domain. Two OADM designs are typically used. One is based on the demultiplexer, space switch and the multiplexer [22]. The other is based on the Fiber Bragg Grating with an optical circulator [22]. In OADM's based on mux/demux the composite signal is first separated out using a demultiplexer and then wavelengths carrying the signal for the specific node are added or dropped through a 2x2 Space Switch. Thereafter the transit wavelengths and added wavelengths are recombined through a multiplexer. However this configuration increases node losses, which in turn would increase the need for optical amplifiers. With this in mind the proposed all optical multicast system employs a low loss OADM based on Fiber Bragg gratings, which was proposed earlier in [22]. This is depicted in Fig 10.

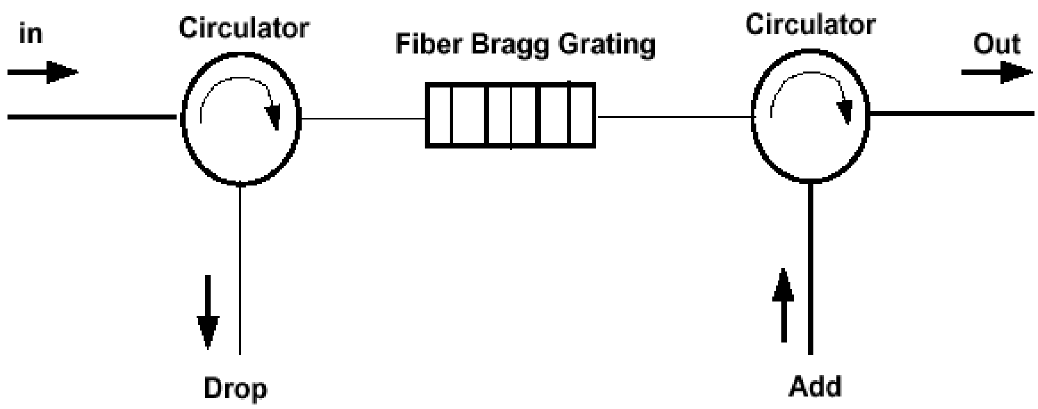

Fig 10: An OADM based on Fiber Bragg Gratings

The function of a grating is that if it is tuned to a specific wavelength it reflects back that wavelength and passes the remaining wavelengths through. Multiwavelengths pass the first circulator and are incident on one or series of gratings. With the grating the tuned wavelengths are reflected back, enter the first circulator again and drop. The added signals enter the second circulator and then one or series of gratings. They are reflected back and merge with the transit wavelengths to form the final composite signal. When more wavelengths and fibers are added to optical networking nodes Optical Cross connects are preferred to OADM's as they can provide a variety of functionalities such as bandwidth management, network restoration and routing. However in light of factors such as immediate component availability off the shelf and cost effective implementation, OADM's were preferred for the all optical multicast systems that were simulated in this thesis. Optical Cross connects would offer great benefits in the context of scalability to next generation Optical networks.

Apart from the devices discussed so far in this chapter, there are other fundamental optical components (which are part of many other devices) such as multiplexers and demultiplexers, which are employed at the transmitter and receiver end in order to enable WDM.

3.2 Optimum Optical Amplifier placement and Effect of Optical Amplifier Placement on SNR, ASE noise

The chosen Optimum Optical Amplifier placement scheme aims at reducing cost and minimizing the number of optical amplifiers used along the network. A simplistic real world model based on [1,7] is presented below to illustrate the approach adopted in choosing distances between optical amplifiers.

Consider a system of total length "L" with amplifiers spaced "d" km apart. The loss between two stages is $e^{-\alpha d}$ where α is the fiber attenuation. Each amplifier adds some spontaneous emission noise. The spectral density of the noise induced by amplified spontaneous emission in an optical amplifier is given by $S_{ASE} = \eta_{sp} h f_c (G-1)$ where G is the gain of the optical amplifier and the ASE noise power in the optical bandwidth B_0 is determined to be $P_{ASE} = \eta_{sp} h f_c (G-1) B_0$. The optical signal to noise ratio at the receiver is given by OSNR = Psig/ P_{ASE} . Each optical amplifier along the chain adds spontaneous emission noise and hence the optical signal to noise ratio degrades along the chain. Given a desired optical signal to noise ratio, the launched power P must satisfy $P >= (OSNR)\ 2P_n B_0 (e^{\alpha d} - 1) L/d$ [1], where OSNR-Optical Signal to Noise Ratio, B_0 – Optical Bandwidth, $P_n = 2\eta_{sp} h f_c$ (η_{sp}-spontaneous emission constant-Planck's constant, f_c-carrier frequency. Typically the launched power P can lie between 0 to 17 mW, but severe constraints are posed by fiber non-linearities when the launched power increases beyond 10 mW. Hence the assumption is that the maximum value that P can take is 10mW. For an OSNR of 25 dB, α = 0.3 dB/km, B_0=20GHz, η_{sp}=2, f_c=192THz, h=Planck's constant=$6.6*10^{34}$ and L=1000Km a few simple calculations are performed to illustrate the process.

- When d=50km, the right hand side of eqn (1) turns out to be 0.208 mW which is less than 10 mW and hence d can be increased further.
- When d=100km, the right hand side of equation 1 turns out to be 5.498 mW which is less than 10 mW and hence d can be increased further
- When d=120km, the right hand side of equation 1 turns out to be 142.81 mW which is greater than 10 mW and hence the optimum value of d is between 100-120km. However this example is fairly simplistic and does not take non-linearities into account. When non-linear effects are ignored the goal is to maximize "d" subject to limitations on transmit power and amplifier output power. In

the presence of non-linearities such as stimulated Raman scattering a factor called as effective length is taken into account [33,34]. This is given by $L_{eff} = (1-e^{-\alpha d}/\alpha)$. L/d for a link of length "L" with amplifiers spaced "d" km apart. In addition a term referred to as Raman gain coefficient comes into the picture which is given by $g\ (\Delta\lambda) = g_R.\ (\Delta\lambda/\Delta\lambda_c)$ (Where $\Delta\lambda$ is the wavelength spacing).

Simulations were performed to study OSNR degradation for various transmit powers and increasing number of optically amplified stages. It is assumed that an amplifier gain of G=20 compensates the fiber loss, η_{sp} is 1.5 and the optical bandwidth is 0.1nm. Results of this analysis are shown in Fig 11.

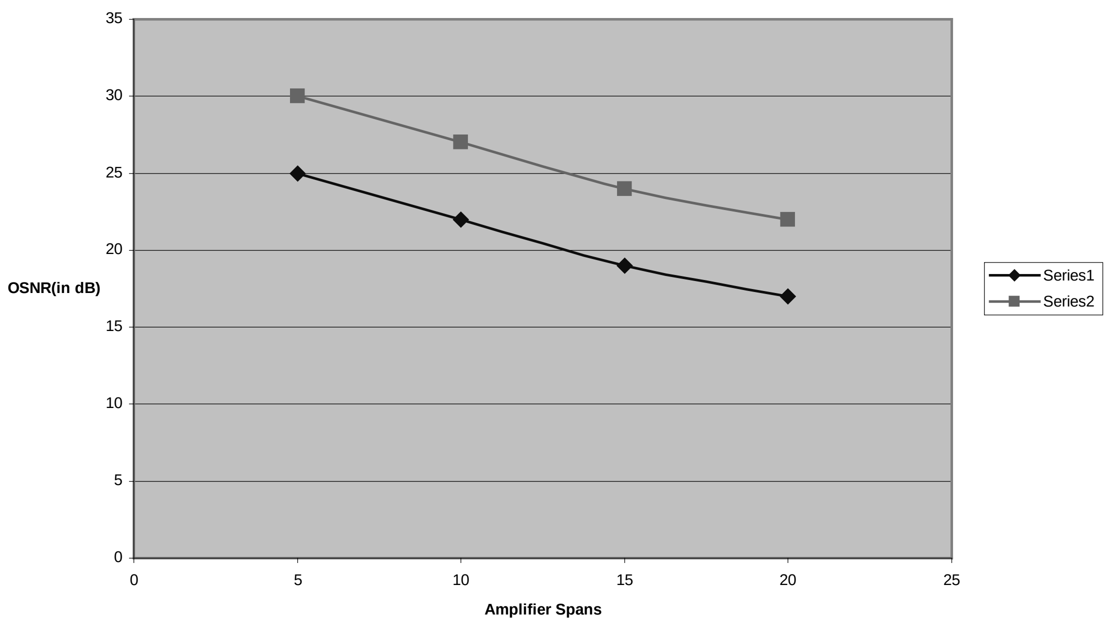

Fig 11: OSNR degradation versus number of optically amplified spans (bottom curve in blue – for a transmit power of –5 dBm, Top curve in pink – for a transmit power 0 dBm)

These results indicate that for transmit powers of –5 dBm and 0 dBm the maximum number of amplifying units that can be supported (for design parameters mentioned above) while maintaining an OSNR greater than 25 dB are 4 and 14 respectively. An OSNR of 20 dB may actually be sufficient but however a higher value is chosen to provide a design margin

Chapter 4: Design and Simulation of the All Optical Multicast System

4.1 Multicast Capable Switching Node and Network Architecture

In addition to signal degrading due to various losses along the fiber there is loss in signal power due to signal splitting too. In order to provide adequate support for multicast in an all-optical network it becomes essential to replicate copies of the signal at various switching nodes along the network. We are looking primarily at using two classes of switches along the network-1) multicast capable, and 2) multicast incapable. An optical splitter splits the input signal into multiple identical output signals. The multicast capable switches would be based on using optical splitters. Since an optical splitter is a passive device the power of each output signal is 1/n times the input signal. To be detected the signal power needs to be more than a threshold value and hence a network with multicast capable switches may require more number of optical amplifiers. The proposed design for the Multicast capable switch essentially consists of four stages and is similar to [23]. The proposed design is represented pictorially in Fig 12. and also explained in the following paragraph.

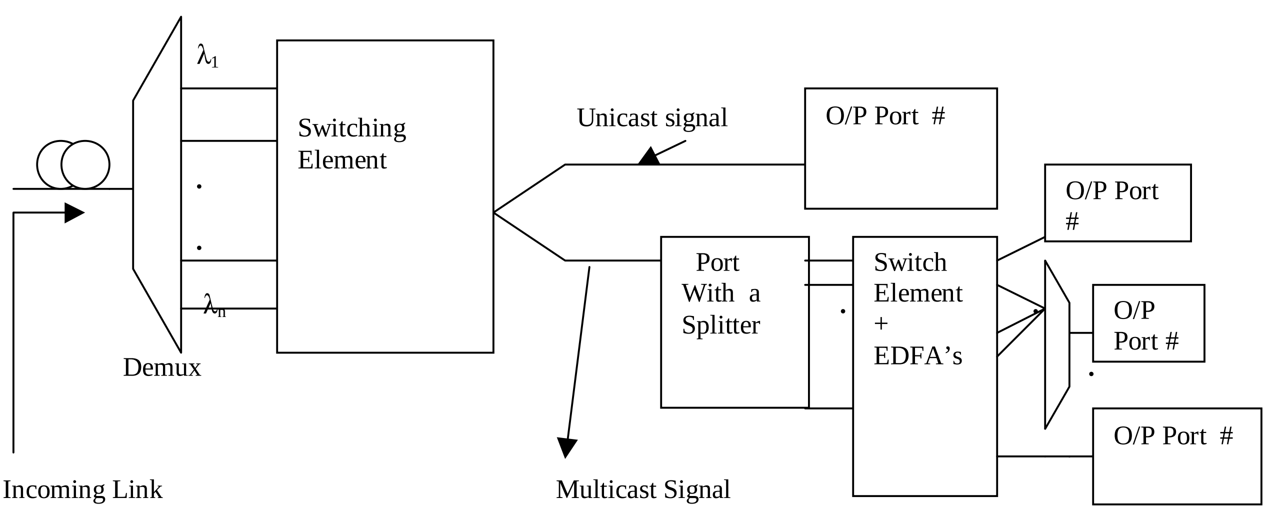

Fig 12: Multicast Capable Switching Node

1. In the first stage the signal in the incoming link is demultiplexed into separate wavelengths each carrying a separate signal.

2. Then the separate signals each on separate wavelengths are switched by a suitable switching element. Unicast signals are sent directly to output ports corresponding to their output links while those signals that need to be multicast are sent to a port connected to a splitter.

3. In the third stage the output of the splitter is connected to a switch which routes the multicast signals to their respective output links. (After amplification as desired)

4. Finally in the fourth stage optical signals which are destined for the same output link but are on different Wavelengths are multiplexed and then sent on the output link.

For reasons already explained in chapter 3 optical add/drop multiplexers are chosen as switching elements for the all optical multicast system proposed in this thesis.

Network Architecture

The number of splits that can be supported in an all-optical multicast system is dependent on the link length, length of the distribution fibers from the split point to the destination terminals and also on the placement details of the EDFA's used along the link. Multicast routing algorithms are aimed at primarily minimizing the number of multicast capable nodes that are traversed by light trees, minimizing the number of splitters located at each node while maximizing performance gain from the power splitters used and minimizing wavelength blocking probability. The goal of the analysis performed in this effort was to obtain an estimate of the number of splits that could be supported for optical link backbones of various lengths independent of the specific node and network configuration. While it is extremely difficult to achieve the above stated objective in its entirety, one can exploit the fact that most metropolitan area networks typically consist of a long optical backbone link running through the entire terrestrial area with short lengths of distribution fiber used to provide access or service to the client terminals [6]. With this in mind the proposed all optical multicast systems are designed for various optical backbone link lengths with the splits to the destination terminals accomplished through relatively short lengths of distribution fiber.

This is depicted pictorially in Fig 13 and Fig 14 below. Fig 14 shows the simulation framework where the premise is that one of the signal copies traverses the entire optical backbone while the other signal copies are sent to destination terminals whose distances from the split points are much smaller compared to the total link distance and hence don't require additional amplifying units.

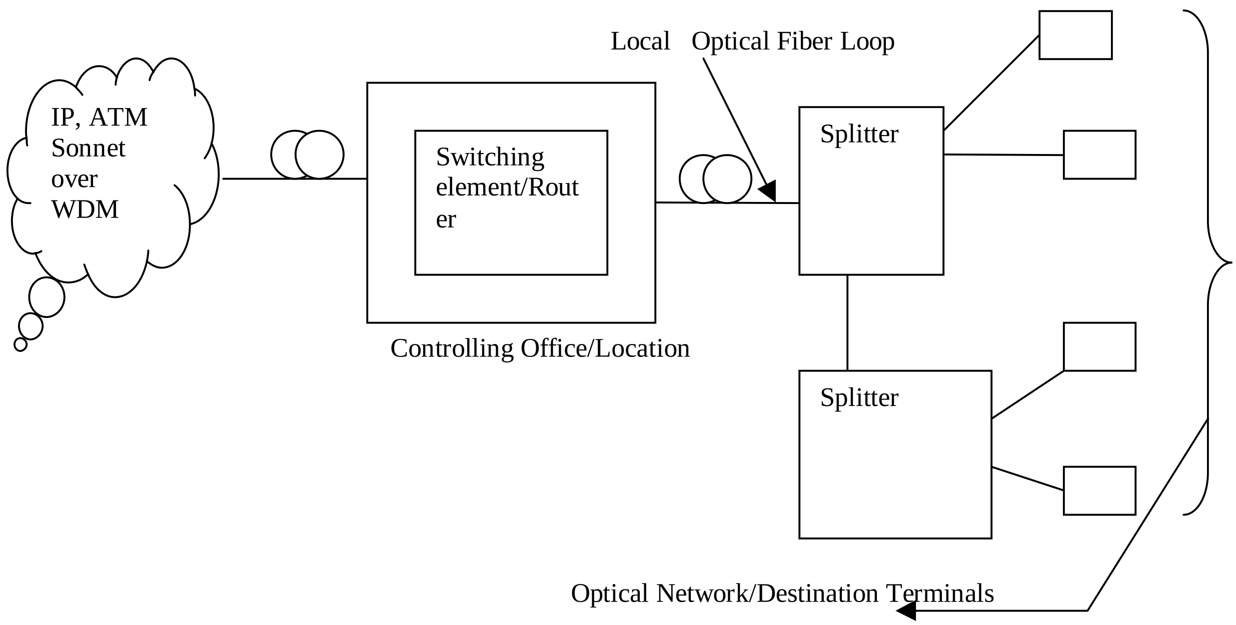

Fig 13: A typical Metropolitan Area Network

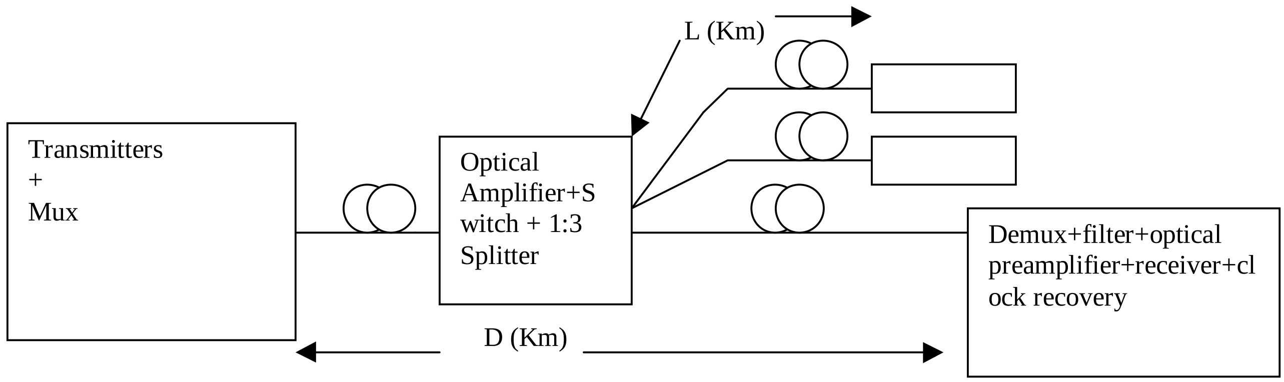

Fig 14: Simulation Framework for the proposed network (where D>>L)

4.2 Modified Optical Amplifier Placement scheme for All Optical Multicast

The optical amplifier placement for all optical multicast is primarily based on the approach already discussed in the last section of chapter 3. However in all optical multicast applications the number of splits that can be supported can be increased to a certain extent by deviating from the optimum optical amplifier placement scheme discussed previously. A greater number of optical amplifiers within a given distance does not deteriorate optical signal to noise ratio as the interspan loss between amplifying units reduces and this takes higher precedence over he influence of the number of optically amplified spans. This point is illustrated in the following paragraph.

The effect of SNR on optical amplifier placement can be modeled adequately by the equation below

SNR = 55+P_{out} - L - 10logN [6], where N – number of spans, L – interspan loss

For a 500 Km link with L = 25 dB, N=5, P_{out} = 0 dBm SNR turns out to be 23.02 dB. For the same link when we have L=12.5 dB, N=10,P_{out}=0 dBm we get SNR = 32.5 dB. This equation ignores the effect of non-linearity, however the trend remains the same in the presence of non-linearity. Based on the discussions in the preceding two paragraphs and the section on optical amplifier placement in chapter 3 the optical amplifier placement scheme is modified and this is depicted in Fig 15. The number of optical amplifiers within the link span are doubled from the number originally arrived upon using the optical amplifier placement scheme. Increasing the number of optical amplifiers beyond this point produces reduced dividends (in terms of # of splits) due to output power and gain saturation effects in cascaded EDFA's. This occurs primarily due to drooping gain profile characteristics of EDFA' with increasing input optical power. These effects are relatively well understood and it is not the intent of the thesis to discuss these issues at length. Detailed discussion can be found in [1].

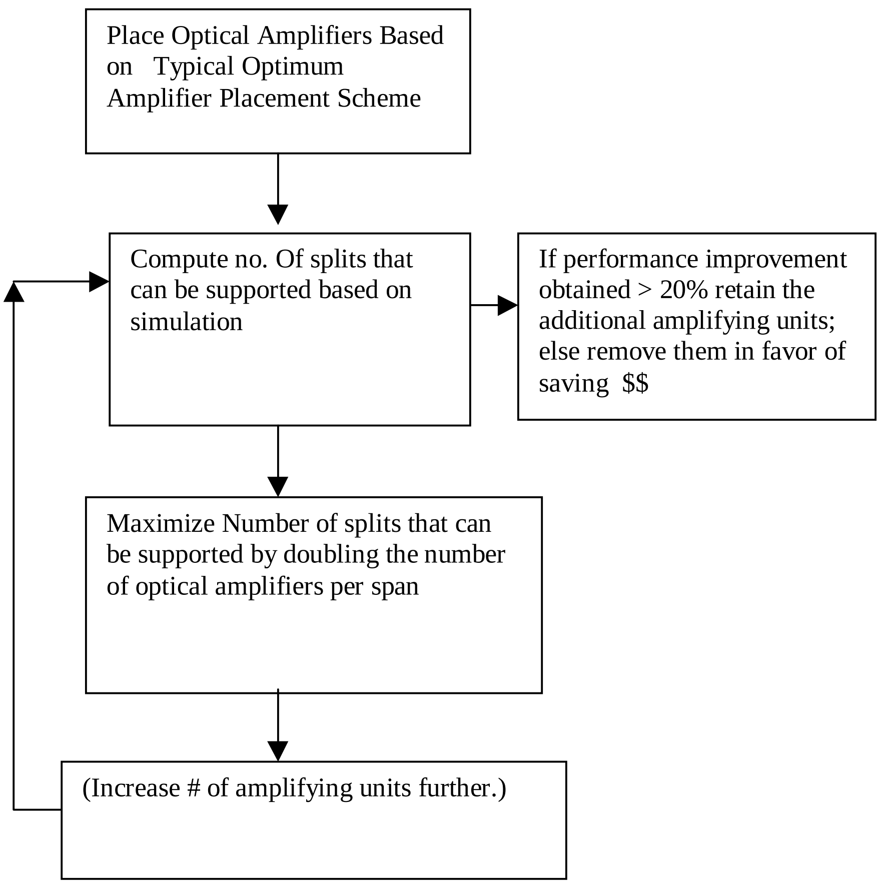

Fig 15: Modified Optical Amplifier Placement Scheme

4.3 SNR , Gain and Power Transients in Optical Amplifier Chains

There are a good number of performance issues to study in optical amplifier chains. Some of the relevant issues such as optimum optical amplifier placement and the effect of optical amplifier placement on SNR and ASE noise have already been dealt with in the previous section and in the last section of chapter 3. In real world networks sizeable system impairments may result from channel addition or loss in a point-to-point communication link composed of a long chain of EDFA's. Hence it is important to study transient time behavior for cascaded EDFA's to the gain or loss of one or more wavelength channels in a WDM system before determining the system's feasibility in the long run. In this section results obtained from time transient analysis of cascaded EDFA's are presented.

The dynamic behavior of the EDFA is obtained by the model introduced in [24] and is based on solving a single ordinary differential equation (ODE) into which ASE is included. To study time transient behavior a sixteen-channel WDM channel is built with1.6nm wavelength spacing and –7 dBm input power. The system consists of 20-cascaded EDFA's. Forward pumping at 980 nm, a pump power of 18 dBm and a fiber length of 15.0 m are assumed for the EDFA's. A pass band filter is inserted after each amplifying unit to block the propagation of forward ASE. Fig 16 shows the schematic for the system built to study transients caused by a single power discontinuity. Fig 16 shows only amplifier block, which is depicted by a triangle. The loop parameter in the simulation was set to 20 to build many such identical sections. Fig 17 and Fig 18 summarize the graphical results depicting SNR and power excursions as a function of time and number of cascaded EDFA's.

The results obtained show that there are significant SNR and power excursions of about 3.5 dB and 4 dB respectively after twenty amplifier units in the amplifier chain after about only 100 microseconds. Hence it would be important to design the system with an error margin in order to account for real world uncertainties.

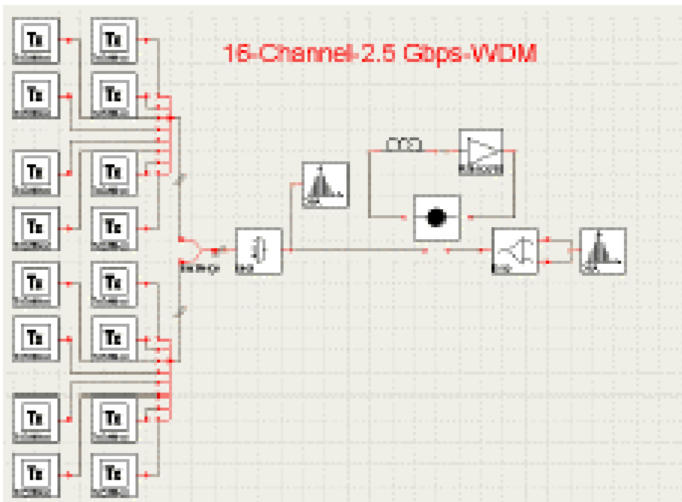

Fig 16: Sixteen-channel WDM system with 20-cascaded EDFA’s (only one edfa is shown, but the loop parameter in the simulation is set to 20, the passband filter is also built internally into the composite EDFA model)

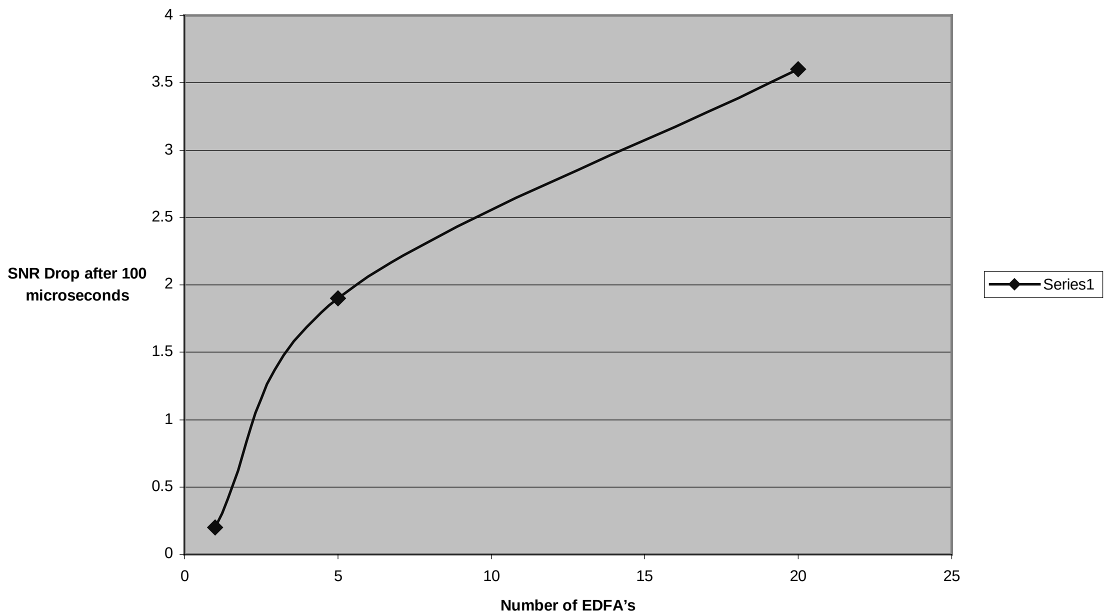

Fig 17: Graph showing SNR drops at the end of the 1st, 5th and 20th EDFA in the optical amplifier cascade after 100 microseconds

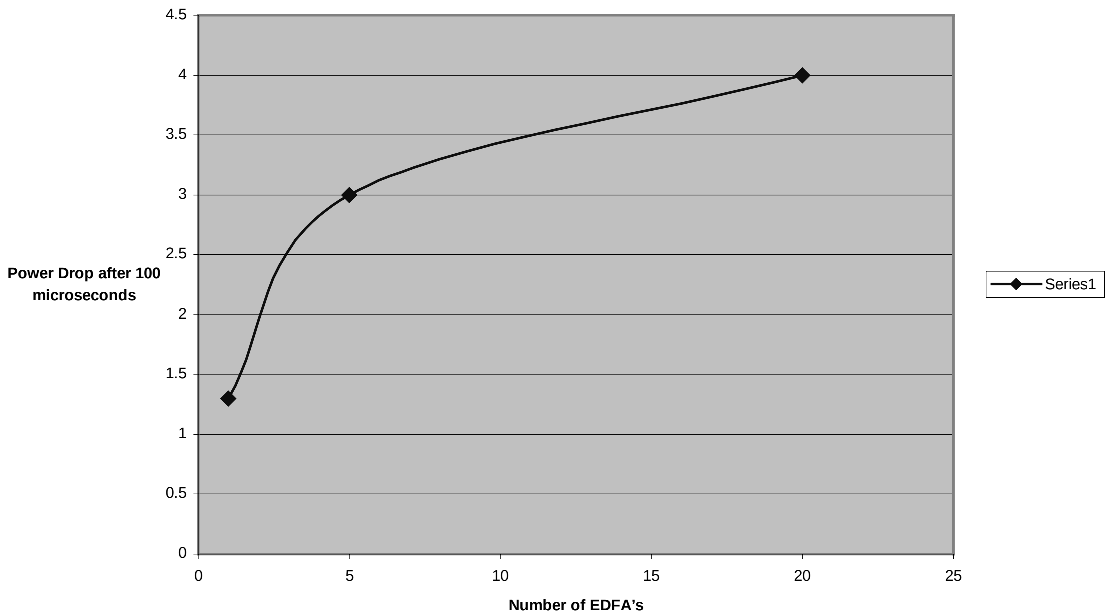

Fig 18: Graph showing Power Drops at the end of the 1st, 5th and 20th EDFA's after 100 microseconds

Gain dynamics and Output Power Variations in Optical Burst Switched Networks

The end application for the proposed all optical multicast system is in optical burst switched networks. When Optical bursts are transmitted through a chain of EDFA's dynamic gain changes occur which in turn produce large variations in output power at the end of the data channels. In this section a few preliminary simulation results are presented to understand these effects. EDFA's are usually operated in saturation and when they are in strong saturation the output power is nearly constant and independent from the input optical power. However things become very different when they are operated in networks with data bursts that are randomly turned on or off.

The input signal of each channel is modeled as a sequence of data transmission (on/burst period) and off periods to simulate optical bursts. Simulations were performed to study the power spectrum fluctuations for a single EDFA with three different burst lengths/off periods and for a chosen burst length/off period in EDFA cascades as a function of the number of EDFA's. The parameters chosen for the EDFA in the simulation are similar to those chosen in the previous analysis. The results obtained are summarized in Fig 19 and Fig 20. These results indicate that power excursions increase along the optical amplifier chain and also increase with the length of the on/off periods. For shorter on/off periods the power excursion is relatively small on account of less time to react to gain variations. A greater power excursion is also observed when the off period is more relative to the burst period as the average power is smaller and there is more time for gain to increase to a higher value. In order to address these issues excellent gain control methods such as the one listed in [25] needs to be employed for stabilizing the Optical Amplifier gain in dynamic real world networks

Burst Period	Off Period	Power Drop
50us	50us	2.8 dB
50us	250us	6 dB
1ms	1ms	4.5 dB

Fig 19: Power Drops encountered in a single EDFA for various burst periods.

No. of EDFA's	Power Drop
2	4.8 dB
4	7 dB
6	11 dB

Fig 20: power drops in cascaded edfa chains for a burst and off period of 1ms and 150us respectively

4.4 Simulation Model for All Optical Multicast and Results

A wide variety of multicast networks were simulated using the CAD tool from Virtual Photonics to determine the feasibility of multicasting in all optical systems. The base network was essentially a 2.5Gbps, 16 channel WDM system with splits simulated using 1:2 and 1:8 splitter models and inline EDFA's placed at 100Km spans to compensate for losses.

The base schematic for the WDM system built to study multicasting is shown below in Fig 21. The chosen component characteristics as well as the simulation approach are also outlined in this section. The number of splits that can be supported along a link depends to a certain extent on the division of the splits along the link. In order to obtain results independent of the organization of the splits along the network, the position of the optical splitters shown in the schematic below was varied iteratively over a large range of values and the best case results are presented towards the end of this section.

Every component in the system has a variable performance (specified by mean and standard deviation values) and it is necessary to design the system with these variations in mind. It may be a waste of capacity to design a system to cope with every component having it's worst case value. The tool models process variations and the results presented in this section are obtained to 3-sigma confidence levels (99.9%). This means that on an average 99.9% of the network terminals (i.e. 99.9% of the split points or the destination terminals along the length of the network) will receive a signal with an acceptable SNR and BER of about 20dB and 10e-9 respectively. Eye diagrams obtained at the receiver end are also used as performance metrics in the analysis.

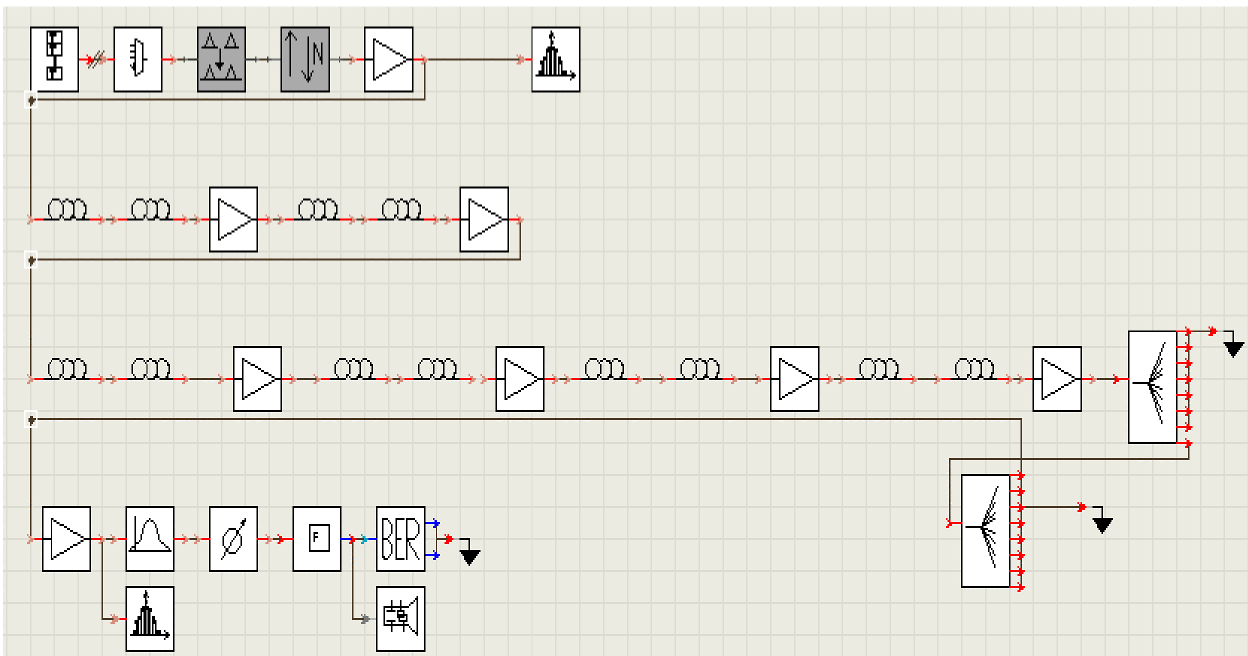

Fig 21: Base Network for studying Multicast to determine number of splits for various link lengths as a function of the number of EDFA’s

Parameters chosen for components in the simulation

Transmitter - 16 wavelengths ranging from 1538.2 nm to 1562.2 nm with 1.6 nm spacing. The output power of each source is 0dBm with an extinction ratio of 10 dB. Each source is assumed to be modulated with a PRBS (pseudo-random bit sequence) at 2.5 Gbits/s. Though the inter-channel spacing and the bit rate chosen may be rather conservative it gives an idea of how things will change when these factors are scaled up progressively. While arriving at the number of splits that can be supported the output power of the sources are varied between –5dBm to 10dBm to obtain best-case results.

Passive Losses -. These losses represent fiber loss, splitter loss, and splice loss. The splitter model assumes that a 1: 2 split results in a loss of 3.5 dB and this extends as per computation to 1:N splitter models.

Optical Fiber - The Fiber parameters used in the simulation are the same as those mentioned earlier in chapter 3. NZDSF+DCF fibers are used.

Erbium Doped Fiber Amplifier - The fiber amplifiers specified for use in the system are gain controlled and Wavelength flattened with a small signal gain of 20 dB, noise figure of 5 dB and a saturated output power of +18 dBm. The fiber length is chosen to be 14.0m .The amplifier models are based on an average power analysis technique [26], which accounts for both forward and reverse propagating ASE noise. Gain control is accomplished by reflecting a small quantity of ASE at a defined wavelength back into the cavity [25]. This causes lasing and hence a clamping of the population inversion which defines the gain at all wavelengths. Gain flattening is achieved by placing a filter within the amplifier having a loss approximately equal to the inverse of the gain spectrum. The EDFA parameters such as fiber length (which influences gain) are varied to obtain best-case results for the all-optical multicast system.

Optical Preamplifier and Booster Amplifier - EDFA's are used at the receiver end and the transmitter end to serve as preamplifiers and power (booster) amplifiers respectively to obtain increased sensitivity at the receiver end

Optical Filter – A fabry perot optical filter is used to select the required wavelength and it is designed to have a bandwidth of 1nm. The in-band insertion loss is set equal to 0 dB as loss associated with this filter is accounted for in the passive losses. The out of band insertion loss is set high at 50 dB as crosstalk effects are considered separately. An optical filter used at the receiver end after the preamplifier can aid in the suppression of ASE noise.

Receiver - The receiver sensitivity is set to –25 dBm for 10-9 BER at a bandwidth of 2.5 Gbps. The maximum power allowed on the receiver is –10 dBm. The electrical SNR and BER are measured at the receiver end and at other split points along the network by placing OSNR probes specific to the all-optical tool at the appropriate points.

A filter and attenuator are used at the receiver end to serve as a demultiplexing unit. An optical add/drop multiplexer was also used at the receiver end in some of the simulations but this is not depicted in the schematic above.

The multicast systems were simulated for fiber optic link lengths of 600 km and 1000 km, which fall in the category of medium haul and long haul systems respectively. Results obtained using 1:2 splitters are presented in Fig 22, Fig 23, and Fig. 24 and Fig 25 respectively. The analysis was also repeated with 1:8 splitters and the results obtained were similar.

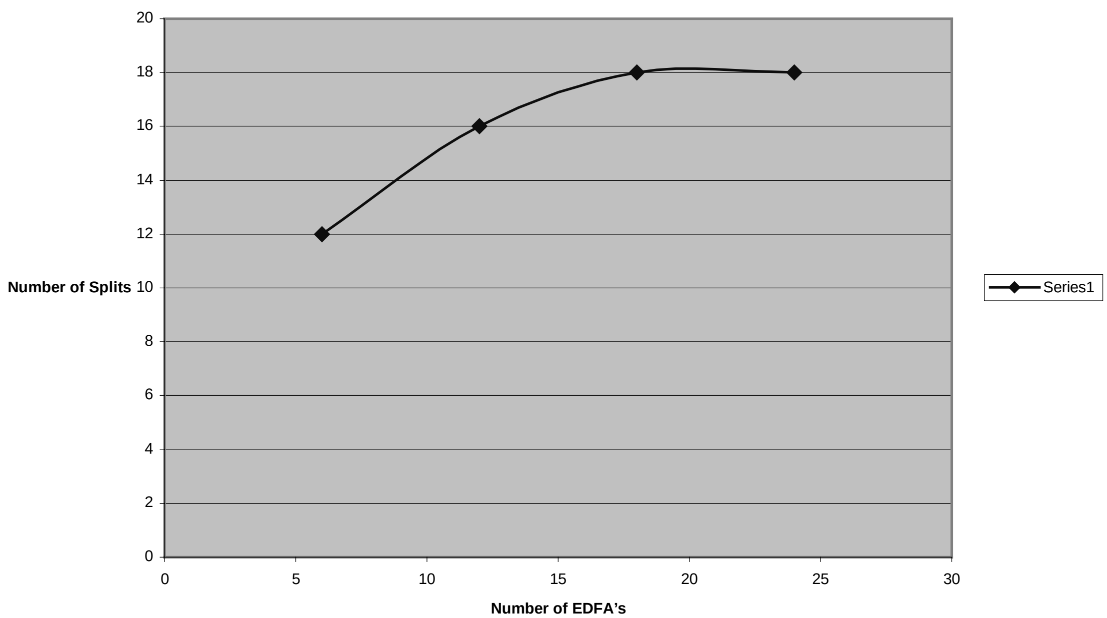

Fig 22: Number of Splits that can be supported for a 600km link as a function of the number of EDFA's

From the graph it is evident that for a 600km link at least 12 splits can be supported as long as there are atleast 6 amplifying units in the longest span. The number of splits that can be supported can be increased upto 18 by increasing the number of amplifying units. However the number of splits that can be supported cannot be increased beyond 18, no matter how many amplifying units are employed, as limits are placed by output power saturation effects and SNR transients encountered in cascaded EDFA chains.

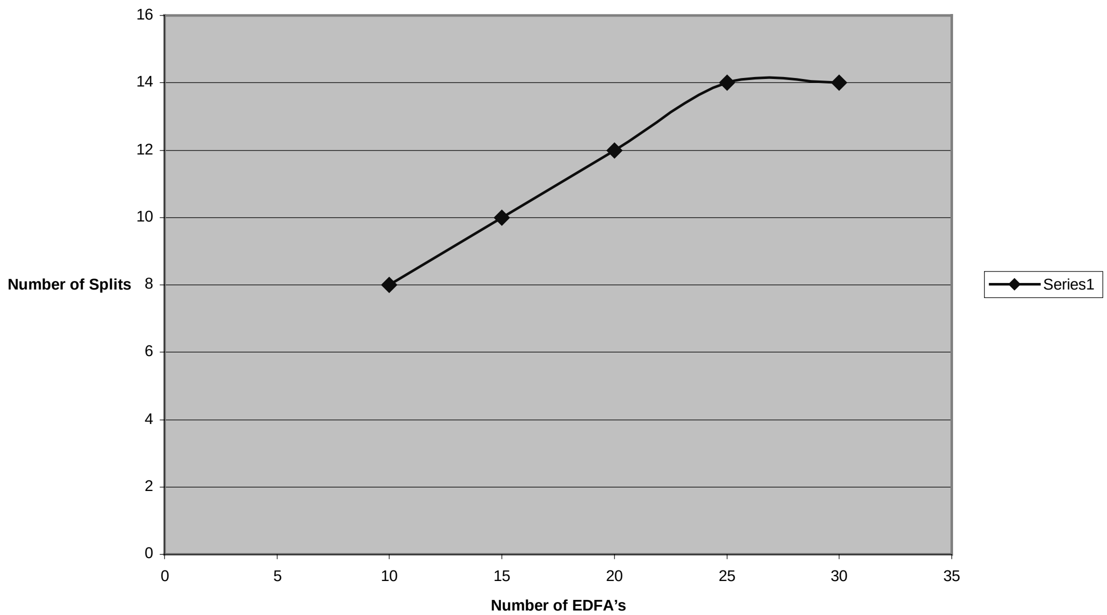

Fig 23: Number of splits that can be supported for a 1000Km link as a function of number of EDFA's

For a 1000km link atleast 8 splits can be supported when there are atleast 10 amplifying units in the longest span. However not more than 14 splits can be supported, no matter how many amplifying units are used. In addition to constraints placed by output power saturation and time transient behavior of cascaded EDFA's, the constraints placed by non-linearities are more severe at these distances.

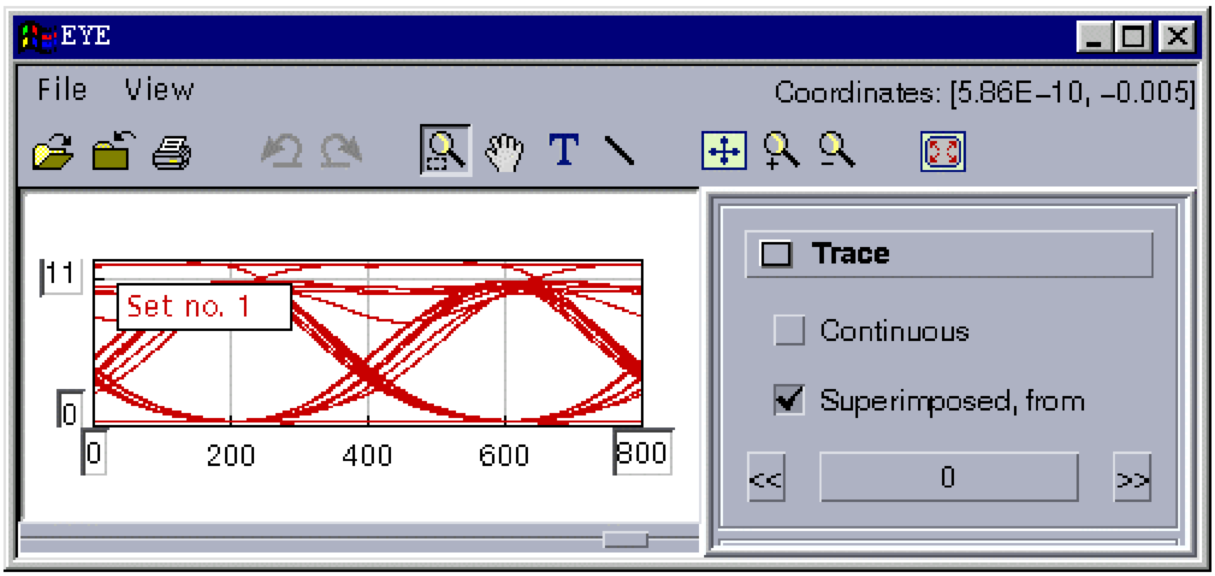

Fig 24: Eye Diagram obtained for a selected channel in the 600km link with 18 splits supported

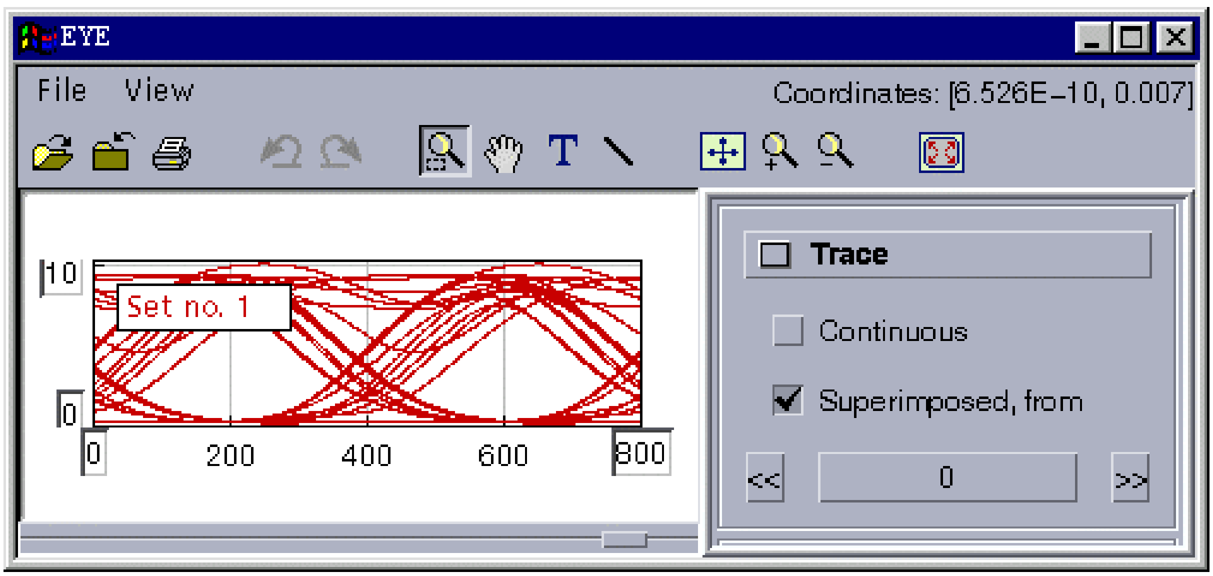

Fig 25: Eye diagram obtained for a selected channel in a 1000km system with 14 splits supported

4.5 Scalability issues for the All Optical Multicast System

As we approach higher bit rate systems of the order of 10 Gbps per or 40 Gbps per channel distances that can be supported are more severely limited by non-linear distortion and dispersion related effects. Dispersion effects do not increase linearly, rather they increase with square of the transmission speed and dispersion related effects worsen transmission by 16 times for 10 Gbps transmission rate per channel compared to 2.5 Gbps. To support long haul distances higher order dispersion management schemes other than using NZDSF+DCF's may be required as these fibers are subject to performance deterioration at increased bit rates and distances due to increased non-linear effects.

As the number of wavelength channels to be supported increases issues such as EDFA gain flatness become more prominent. While gain equalizing filters can be used in theory to stabilize the gain, they are difficult to manufacture to high precision and also the specifications for the required filter is highly dependent on the gain and the number of wavelength channels (which should ideally be upgradeable). Another issue with a larger number of wavelength channels is choosing the optimum channel spacing to minimize cross phase modulation and crosstalk effects.

Chapter 5: Conclusions and Future Work

In this thesis, an approach has been demonstrated to support all optical multicast in WDM transmission systems through the proper choice and deployment of optical hardware components available off the shelf. The immense potential to support all optical multicast offered by deployment of 1:2 and 1:N optical splitters and proper placement of inline EDFA's is clearly highlighted. Tradeoffs in choosing various components and strategies for enabling all optical multicast are discussed at length in this thesis. The dynamic behavior of real world networks due to power discontinuities and optical burst switching is also addressed in this thesis.

The simulation results obtained indicate that multicast support can be made feasible for link lengths of 500-600km with relative ease and also extended for distances upto 1000Km. For long haul distances and higher bit rates limits are placed on multicast support by output power saturation and time transient behavior of cascaded EDFA's as well as fiber non-linearities. For distances greater than 1000Km more involved design approaches involving the use of multi stage amplifier designs, coding / modulation strategies to suppress non-linear effects, error correction codes and improved noise suppression schemes in cascaded EDFA's would be required.

Future work in this area could be directed in extending the system to long haul and ultra long haul systems through the deployment of a combination of EDFA's, Raman Amplifiers and Error correction codes. As network complexity increases it would also be worthwhile to analyze multicast effects for various specific network architectures to achieve improved performance. It would also be good to build relatively short subsections of the proposed system in the laboratory and achieve good correlation between simulated and measured results to obtain increased confidence in the chosen design methodology.

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