İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

EFFECT OF RECONFIGURATION ON IP PACKET TRAFFIC IN WDM NETWORKS

M.Sc. Thesis by

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Programme: Computer Engineering

OCTOBER 2007

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Date of submission : 13 September 2007

Date of defence examination: 18 October 2007

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OCTOBER 2007

<u>İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ</u>

WDM AĞLARINDA YENİDEN KONFİGÜRASYONUN IP PAKET TRAFİĞİNE ETKİSİ

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Tezin Enstitüye Verildiği Tarih : 13 Eylül 2007

Tezin Savunulduğu Tarih : 18 Ekim 2007

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EKİM 2007

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ABBREVIATIONS

ARP	: Address Resolution Protocol
ATM	: Asynchronous Transfer Mode
EDFA	: Erbium-Doped Fiber Amplifier
EGP	: External Gateway Protocol
FDDI	: Fiber Distributed Data Interface
GA	: Genetic Algorithm
GMPLS	: Generalized MultiProtocol Label Switching
ICMP	: Internet Control Message Protocol
IGP	: Interior Gateway Protocol
ILP	: Integer Linear Program
IP	: Internet Protocol
LAN	: Local Area Network
LED	: Light Emitting Diode
MAN	: Metropolitan Area Network
MEMS	: Micro-Electro-Mechanical Systems
MILP	: Mixed-Integer Linear Program
MTU	: Maximum Transmission Unit
OXC	: Optical Cross-Connect
PMD	: Polarization Mode Dispersion
PON	: Passive Optical Networks
RWA	: Routing and Wavelength Assignment
SDH	: Synchronous Digital Hierarchy
SOA	: Semiconductor Optical Amplifier
SONET	: Synchronous Optical Network
TCP	: Transmission Control Protocol
TTL	: Time To Live
TDM	: Time Division Multiplexing
UDP	: User Datagram Protocol
VPN	: Virtual Private Network
VTD	: Virtual Topology Design
VTR	: Virtual Topology Reconfiguration
WAN	: Wide Area Network
WDM	: Wavelength Division Multiplexing

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SUMMARY

Today, both the amount of people accessing communication networks and new communication applications which require high data transfer rates are exponentially increasing. Growing traffic demands triggered the design of optical communication networks which will be able to provide larger bandwidth utilization. Wavelength Division Multiplexing (WDM) was proposed to solve speed mismatch problem between electronics and optics by providing an efficient bandwidth utilization of fiber technology. WDM simply divides immense bandwidth of a single fiber into non-overlapping subchannels for concurrent transmission of optical signals.

A lightpath, which can span multiple fiber links, provides communication channels over the underlying optical communication infrastructure. Lightpath establishment is performed by routing a lightpath through the physical topology and assigning an optimum wavelength from a set of available wavelengths. This procedure is called as Routing and Wavelength Assignment (RWA), which is a NP-complete problem, and divided into subproblems to derive feasible solutions. Virtual Topology Design (VTD), which both contains RWA and routing of traffic requests over virtual topology, means establishment of a set of lightpaths under a given traffic pattern. A change in traffic pattern may trigger reconfiguration decision. Virtual Topology Reconfiguration (VTR) contains determination of a new virtual topology and migration between the old and new virtual topologies.

In this thesis, the effects of virtual topology reconfiguration on Internet Protocol (IP) packet traffic on IP over WDM networks were studied. For this purpose, an IP simulator which is unaware of lower level communication infrastructure was implemented based on Fishnet project. Various reconfiguration algorithms were implemented and tested on developed IP simulator. Packet delays/losses are investigated during reconfiguration procedure for performance comparison of implemented reconfiguration algorithms.

WDM AĞLARINDA YENİDEN KONFİGÜRASYONUN IP PAKET TRAFİĞİNE ETKİSİ

ÖZET

Günümüzde iletişim ağlarına erişen insan sayısı ve iletişim uygulamalarının ihtiyaç duyduğu band genişliği ihtiyacı hızla artmaya devam etmektedir. Artan trafik istekleri daha geniş band genişliği kullanımına olanak verebilen optik iletişim ağlarının tasarımını tetiklemektedir. WDM teknolojisi, fiber teknolojisine ait band genişliğini etkin bir biçimde kullanarak elektronik ve optik domen arasındaki hız farklılığı problemini çözmek için ortaya atılmıştır. WDM, tek bir fibere ait devasa band genişliğini birbiriyle örtüşmeyen alt kanallara bölerek optik işaretlerin eş zamanlı iletimini sağlayan bir teknik olarak tanımlanabilir.

Bir veya daha fazla sayıda optik fiberi kapsayabilen bir ışıkyolu, alt katmanda yer alan optik altyapının üzerinde iletişim kanalları oluşturmaktadır. Işık yolu kurulumu, fiziksel topoloji üzerinde bir ışık yolunun yönlendirilmesi ve uygun dalgaboyları kümesinden bir dalgaboyunun seçilip ilgili ışıkyoluna atanmasıyla gerçekleştirilir. Polinom zamanlı ifade edilemeyen bu yöntem yönlendirme ve dalgaboyu atama (RWA) olarak adlandırılır ve uygulanabilir sonuçların elde edilebilmesi için alt problemlere bölünerek çözülür. RWA ve trafik isteklerinin oluşan sanal topoloji üzerinde yönlendirilmesini içeren sanal topoloji tasarımı, verilen bir trafik örneğine göre bir grup ışık yolunun seçilip kurulması olarak tanımlanabilir. Trafikte meydana gelecek bir değişiklik yeniden konfigürasyon kararının alınmasına neden olabilir. Sanal topoloji yeniden konfigürasyonu, hem yeni sanal topolojinin belirlenmesini hem de bu yeni topolojiye geçişi içermektedir.

Bu tez çalışmasında IP/WDM ağlarda sanal topoloji yeniden konfigürasyonunun IP paket trafiği üzerindeki etkileri incelenmiştir. Bu amaçla, Fishnet projesini temel alan alt katmanda yer alan iletişim altyapısından habersiz olarak çalışan bir IP simülatörü geliştirilmiştir. Çalışma kapsamında, çeşitli yeniden kofigürasyon algoritmaları gerçeklenmiş ve geliştirilen IP simülatörü üzerinde test edilmiştir. Gerçeklenen sanal topoloji yeniden konfigürasyon algoritmalarına ait paket gecikmeleri/kayıpları incelenmiş ve algoritmaların birbirlerine göre başarımları karşılaştırılmıştır.

1 INTRODUCTION

Recent exponential growth in communication networks' users and variety of bandwidth demanding applications triggered researchers to seek for new high capacity communication architectures and protocols. Today's classical communication networks stand far away from being a solution to this capacity need because of their limited electronic processing speeds. Optical networks seem to be capable of meeting the requirements as a strong candidate for next generation network technology by their high speed, better network performance, functionality and lower cost.

A single optical fiber provides almost a limitless bandwidth of 50 THz. Electronic processing speeds of computer networks are nearly one per thousand of this capacity. This leads to an opto-electronic speed mismatch problem between two layers. Wavelength Division Multiplexing (WDM) was proposed to solve speed mismatch problem by providing an efficient bandwidth utilization of fiber technology. WDM simply divides immense bandwidth of a single fiber into non-overlapping subchannels for concurrent transmission of optical signals. Each subchannel corresponds to a different wavelength that is used at the electronic speed of the end-users. The end-stations thus can communicate using wavelength-level network interfaces.

Physical layer technology of optical networks is built by the participation of several components such as; fiber, optical transceivers, amplifiers, wavelength converters, and switches. Fiber constitutes the transmission line over which the optical signal (laser) transmits. Optical transmitters and receivers placed in the nodes of the network produce optical signals from the electronic signals and reproduce the electronic signals from the optical signals respectively. Optical amplifiers are indented for use to regenerate the amplitude of optical signals up to a certain level in order to prevent from attenuation during transmission. Wavelength converters are placed in the nodes of optical networks and issued to alter the wavelength of an optical signal with λ_i to a new one with λ_j. Switches are also placed in the nodes. They facilitate routing schemes of the data transmitted through the optical network.

Lightpaths constitute end to end optical communication channels between two nodes over the physical topology at an assigned wavelength. A lightpath from source to destination nodes may consist of several fiber lines and optical cross-connects. Routing a lightpath through the physical topology and assignment of an optimum wavelength from a set of available wavelengths is an important problem which is known as RWA (Routing and Wavelength Assignment) problem. RWA is a NP-complete problem; therefore heuristic methods are commonly referenced in the solution of RWA problem. Usually, RWA is divided into subproblems of routing and wavelength assignment. With division of the problem into smaller pieces, two easier subproblems are derived to be solved and optimum subsolutions are searched from these subproblems. Virtual Topology Design (VTD) is the selection and establishment of a set of lightpaths under a given traffic pattern. VTD is also a NP-Hard problem that includes both RWA and routing of traffic requests over newly established virtual topology. The virtual topology on which the current traffic requests have been routed possibly may have performance degradation when varieties in traffic pattern occur. At that time, a new virtual topology considering new traffic pattern must be established. Fortunately, there is an advantage of the optical networks that they are able to reconfigure their logical topology to adapt to changing traffic patterns. This is called Virtual Topology Reconfiguration (VTR) and by definition it contains the problem of VTD. VTR can also be divided into two subproblems of first as determination of new virtual topology and second as transition between old and new virtual topologies.

In this thesis, main goal is to study the effect of virtual topology reconfiguration on IP packet traffic. For this purpose, an IP simulator which is unaware of lower level communication infrastructure was implemented. IP simulator would only create, manage and report transmission of packet traffic according to a given traffic pattern. Several virtual topology reconfiguration algorithms, which are working under previously developed IP framework, were implemented and their performance metrics were evaluated for detailed examination of packet delay or loss on IP layer.

This study will inform us about the effect of reconfiguration at user viewpoint. One additional aim of this thesis is to be able to compare and discuss the performance of various virtual topology reconfiguration algorithms based on the implemented IP framework.

The content of the chapters of this thesis are as follows:

- Chapter 2 explains the hierarchical structure of communication networks first. Then, gives a summary of optical networks by introducing WDM, fiber, transceivers, amplifiers, wavelength converters and switches as the underlying physical components. Basic terminology of optical networks such as lightpath, RWA, VTD, and VTR follows the topics above. The chapter concludes with an extensive literature survey about previous reconfiguration studies.
- Chapter 3 first gives a brief information about Internet Protocol (IP) then introduces the network layer framework (Fishnet) used in the simulations. Chapter 3 concludes with description of modifications and additions on the simulation framework.
- Chapter 4 introduces the virtual topology reconfiguration algorithms used in this study. First, virtual topology design algorithm (GLTDA) employed in virtual topology reconfiguration is described. Then, Longest Path First (LPF), Shortest Path First (SPF) and Minimal Disrupted Lightpath First (MDPF) algorithms are given. Also, an implemented Branch Exchange heuristic is introduced with construction of its auxiliary graphs and matrix formulations.
- Chapter 5 demonstrates simulation environment and results. Physical topology used in simulations and its constraints are first stated. Second, traffic generation technique and generation of network layer packets of Discovery, Link State and Transport types are explained. Various simulation scenarios described and their numerical results are given in the end of this chapter.
- Chapter 6 concludes thesis and gives directions for further research about the subject

2 OPTICAL WDM NETWORKS

This chapter will first introduce Wavelength Division Multiplexing (WDM). Then, chapter will continue with today's telecom network hierarchy. Access, metro, and long-haul networks corresponding to LANs, MANs and WANs respectively will be summarized. Overview of optical components such as fiber, signal amplifiers, lasers, receivers, wavelength converters and optical switches will be the next topic that follows. General terminology about optical networks such as lightpath, routing and wavelength assignment, virtual topology design and reconfiguration will be introduced. The chapter concludes with a literature survey about previous works on virtual topology reconfiguration.

2.1 Wavelength Division Multiplexing

The optical transport layer is capable of delivering multi-gigabit bandwidth with high reliability. The bandwidth available on a fiber is approximately 50 THz (terahertz). Increasing the transmission rates could not be adopted as the only means of increasing the network capacity. Transmission rates beyond a few tens of gigabits per second could not be sustained for longer distances for reasons of impairments due to amplifiers, dispersion, non-linear effects of fiber, and cross-talk. Hence, wavelength-division multiplexing was introduced, which divided the available fiber bandwidth into multiple smaller bandwidth units called wavelengths.

The WDM-based networking concept was derived from a vision of accessing a larger fraction of the approximately 50 THz theoretical information bandwidth of a single mode fiber. A natural approach to utilizing the fiber bandwidth efficiently is to partition the usable bandwidth into non-overlapping wavelength channels. Each wavelength, operating at several gigabits per second, is used at the electronic speed of the end-users. Many users can use such channels simultaneously to transmit and receive data at peak electronic rates, increasing the aggregate network capacity by the number of such channels times the rate of each. Because each user is capable of transmitting data into and receiving data from more than one channel, the transmitters and receivers must be tunable to the different wavelengths in the fiber.

Channel spacing itself is affected by several factors such as the channel bit rates, optical power budget, nonlinearities in the fiber, and the resolution of transmitters and receivers. A large number of wavelengths (>160) packed densely into the fiber with small channel spacing is called Dense Wavelength-Division Multiplexing (DWDM). An alternative WDM technology with a smaller number of wavelengths (<10), larger channel spacing, and much lower cost is termed as coarse WDM (CDWM) **(Ilyas & Mouftah, 2003)**.

2.2 Optical Network Hierarchy

Today's telecom network can be considered to consist of three sub-networks as illustrated in Figure 2.1 access, metropolitan, and long haul. The network topology for access can be a star, a bus, or a ring; for metro a ring; and for long haul a mesh.

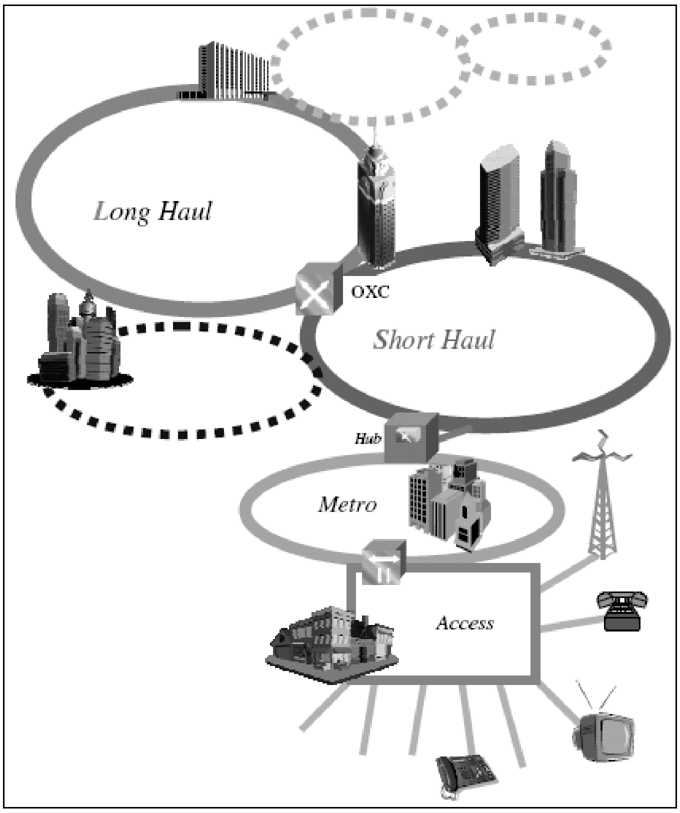

Figure 2.1: Hierarchical View of Optical Networks (Access, Metro, and Longhaul)

2.2.1 Access Networks

Optical access networks cover the "first/last mile" in the geographical topology and usually extend from 3 to 10 km. Access networks connect the service provider central offices to businesses and residential subscribers. Subscribers demand high bandwidth, media-rich and low price solutions from access networks. Today, the bandwidth "bottleneck" has shifted to the first/last mile region, as growing end-user demands continue to drive traffic volumes. Various architectures were proposed to overcome this bottleneck problem such as Passive Optical Networks (PONs), Ethernet PON (EPON) and WDM PON.

2.2.2 Metro Optical Networks

Regional/metro area optical networks span geographical distances about 10 to 500 km and bridge the gap between access and long-haul/backbone optical networks. Many technologies have been considered for metropolitan-area networks. The key requirement of these networks relates to the support for varying traffic types, both old and new.

2.2.2.1 SONET/SDH

SONET/SDH is one of the founding technologies used in MANs, this TDM-based approach has been used for both TDM-based circuit switched networks and most overlay networks. However, cost, scalability, and unresponsiveness to bursty IP traffic limit this technology.

2.2.2.2 ATM

Becoming an integral part of the networking infrastructure, ATM has revolutionized telecommunications. ATM provides a common transmission format for all protocols and traffic types for transmission over a SONET infrastructure. Although IP over SONET (POS) is preferred, ATM still has a strong hold on the metropolitan front. Its major advantages include high-speed line interfaces, efficient virtual circuit services, and traffic management. ATM also accommodates bursty data, voice, and video, making it the preferred choice for such applications.

2.2.2.3 Gigabit Ethernet

Besides being less expensive, it provides the ability to support new applications and data types, and flexibility in network design. Moreover, it allows multiple vendors sourcing and provides interoperability.

2.2.2.4 WDM in Metro Networks

The demand for bandwidth created by new applications, such as e-commerce, packetized voice, and streaming multimedia, has created a bottleneck in the MAN. To some extent, WDM technology has helped to satisfy these demands, and Optical WDM Rings evolved from SONET/SDH concepts were introduced.

2.2.3 Wide Area (Long Haul) Optical Networks

Long haul optical networks locates at the top of the hierarchy and covers the largest geographical area up to 100s-1000s km. Long haul network nodes receive excessive traffic requests from Metro networks and manage the provisioning of these requests among other backbone nodes. The first-generation optical networks that provided high-speed and long-haul transport were based on SONET/SDH. In such optical networks, the data packets are transported at high bit rate in the optical domain over long spans of fiber; however, circuit switching, traffic separation, routing, and protection functions are performed in electronic domain. This requires optical-to electrical and electrical-to-optical (O-E-O) conversions, and thus can handle a single or at the most a few wavelengths. As the bit-rates increased, traffic processing in long-haul transport and, at the intermediate nodes, became a complex, cumbersome, and expensive task. As a result, the optical networks then evolved into their second generation where several routing and switching functions are handled optically with electronic controls with the advent of WDM.

2.3 Optical Transmission Systems

The success of optical WDM networks depends heavily on the available optical device technology. This chapter will present an introduction to some of the optical device issues in WDM networks. It discusses the basic principles of optical transmission in fiber, and reviews the current state of the art in optical device technology.

The first step in the development of fiber optic transmission over meaningful distances was to find light sources that were sufficiently powerful and narrow. The light-emitting diode (LED) and the laser diode proved capable of meeting these requirements. Lasers went through several generations in the 1960s, culminating with the semiconductor lasers that are most widely used in fiber optics today.

In general, there are three groups of optical components.

- Active components: devices that are electrically powered, such as lasers, wavelength shifters, and modulators.
- Passive components: devices that are not electrically powered and that do not generate light of their own, such as fibers, multiplexers, demultiplexers, couplers, isolators, attenuators, and circulators.
- Optical modules: devices that are a collection of active and/or passive optical elements used to perform specific tasks. This group includes transceivers, erbium-doped amplifiers, optical switches, and optical add/drop multiplexers.

2.3.1 Optical Fiber

Fiber possesses many characteristics that make it an excellent physical medium for high speed networking. Figure 2.2 shows the two low-attenuation regions of optical fiber **(Sivalingam & Subramaniam, 2002)**. Centered at approximately 1300 nm is a range of 200 nm in which attenuation is less than 0.5 dB per kilometer. The total bandwidth in this region is about 25 THz. Centered at 1550 nm is a region of similar size, with attenuation as low as 0.2 dB per kilometer. Combined, these two regions provide a theoretical upper bound of 50 THz of bandwidth.

The main requirement on optical fibers is to guide light waves with a minimum of attenuation (loss of signal). Optical fibers are composed of fine threads of glass in layers, called the core and cladding, in which light can be transmitted at about two-thirds its speed in vacuum. The transmission of light in optical fiber is commonly explained using the principle of total internal reflection.

Light is either reflected (it bounces back) or refracted (its angle is altered while passing through a different medium) depending on the angle of incidence (the angle at which light strikes the interface between an optically denser and optically thinner material).

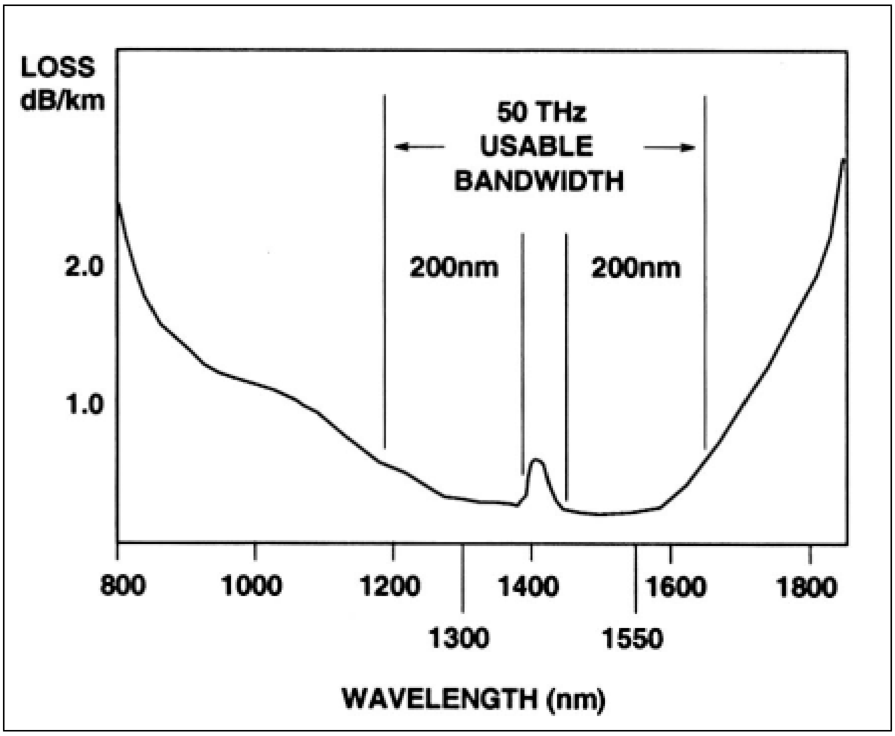

Figure 2.2: Low Attenuation Regions of Optical Fiber

Total internal reflection happens when the following conditions are met:

- Beams pass from a material of higher density to a material of lower density. The difference between the optical density of a given material and a vacuum is the material's refractive index.
- The incident angle is less than the critical angle. The critical angle is the angle of incidence at which light stops being refracted and is instead totally reflected.

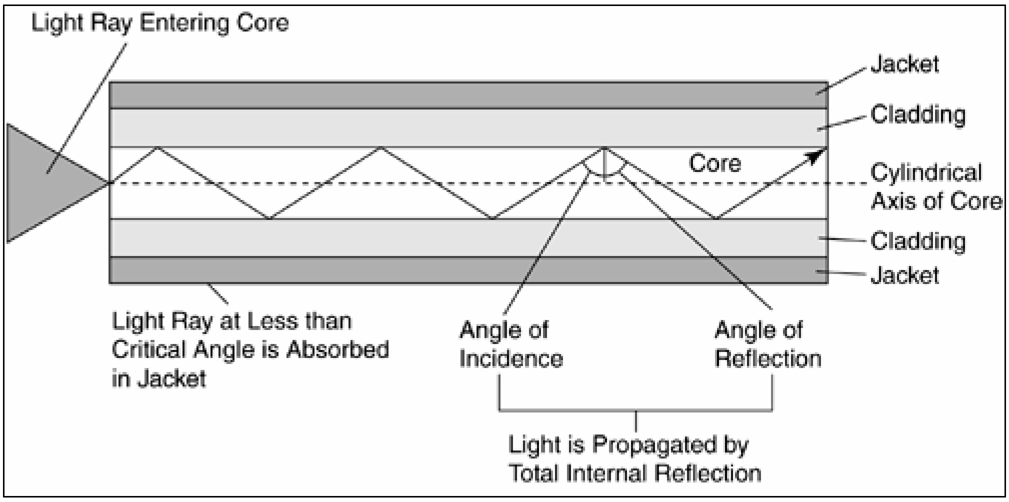

Figure 2.3: Propagation of Light Through a Fiber Optic Cable

An optical fiber consists of two different types of very pure and solid glass (silica): the core and the cladding. These are mixed with specific elements, called dopants, to adjust their refractive indices. The difference between the refractive indices of the two materials causes most of the transmitted light to bounce off the cladding and stay within the core as in Figure 2.3. Two or more layers of protective coating around the cladding ensure that the glass can be kept without damage.

Transmission of light in optical fiber presents several challenges that must be dealt with. These fall into the following three broad categories **Agrawal (1997)**:

- Attenuation: Decay of signal strength or loss of light power, as the signal propagates through the fiber.
- Chromatic dispersion: spreading of light pulses as they travel down the fiber.
- Nonlinear effects: cumulative effects from the interaction of light with the material through which it travels, resulting in changes in the lightwave and interactions between lightwaves.

2.3.1.1 Attenuation

Attenuation in optical fiber is caused by intrinsic factors, primarily scattering and absorption, and by extrinsic factors, including stress from the manufacturing process, the environment, and physical bending. The most common form of scattering, Rayleigh scattering, is caused by small variations in the density of glass as it cools.

Scattering affects short wavelengths more than long wavelengths and limits the use of wavelengths below 800 nm.

Attenuation due to absorption is caused by a combination of factors, including the intrinsic properties of the material itself, the impurities in the glass, and any atomic defects in the glass. These impurities absorb the optical energy, causing the light to become dimmer. While Rayleigh scattering is important at shorter wavelengths, intrinsic absorption is an issue at longer wavelengths and increases dramatically above 1700 nm. Absorption due to water peaks introduced in the fiber manufacturing process, however, is being eliminated in some new fiber types.

The primary factors affecting attenuation in optical fibers are the length of the fiber and the wavelength of the light. Attenuation in fiber is compensated primarily through the use of optical amplifiers.

2.3.1.2 Dispersion

Dispersion is the spreading of light pulses as they travel through optical fiber. Dispersion results in distortion of the signal, which limits the bandwidth of the fiber. Two general types of dispersion affect WDM systems. One of these effects, chromatic dispersion, is linear, while the other, Polarization Mode Dispersion (PMD), is nonlinear.

Chromatic dispersion occurs because different wavelengths propagate at different speeds. In single-mode fiber, chromatic dispersion has two components, material dispersion and waveguide dispersion. Material dispersion occurs when wavelengths travel at different speeds through the material. A light source, no matter how narrow, emits several wavelengths within a range. When these wavelengths travel through a medium, each individual wavelength arrives at the far end at a different time. The second component of chromatic dispersion, waveguide dispersion, occurs because of the different refractive indices of the core and the cladding of fiber. Although chromatic dispersion is generally not an issue at speeds below 2.5 Gbps, it does increase with higher bit rates.

Most single-mode fibers support two perpendicular polarization modes, vertical and horizontal. Because these polarization states are not maintained, there occurs an interaction between the pulses that results is a smearing of the signal. PMD is generally not a problem at transmission rates below 10 Gbps.

2.3.1.3 Nonlinear Effects

In addition to PMD, there are other nonlinear effects. Because nonlinear effects tend to manifest themselves when optical power is very high, they become important in DWDM. Linear effects such as attenuation and dispersion can be compensated, but nonlinear effects accumulate. They are the fundamental limiting mechanisms to the amount of data that can be transmitted in optical fiber. The most important types of nonlinear effects are stimulated Brillouin scattering, stimulated Raman scattering, self-phase modulation, and four-wave mixing **(Agrawal, 1997)**. In DWDM, four-wave mixing is the most critical of these types. Four-wave mixing is caused by the nonlinear nature of the refractive index of the optical fiber. Nonlinear interactions among different DWDM channels create sidebands that can cause interchannel interference. Three frequencies interact to produce a fourth frequency, resulting in cross talk and signal-to-noise level degradation. Four-wave mixing cannot be filtered out, either optically or electrically, and increases with the length of the fiber. It also limits the channel capacity of a DWDM system.

2.3.2 Optical Amplifiers

Optical signals undergo degradation when traversing optical links due to dispersion, loss, cross talk, and nonlinearity associated with fiber and optical components. Optical amplifiers are systems that amplify signals in the optical domain as opposed to repeaters which amplify after conversion to the electrical domain. This type of amplification, called 1R (regeneration), does not perform reshaping or reclocking and thus provides total data transparency. A single amplifier can simultaneously amplify all wavelengths and consequently avoids the overhead of one amplifier per channel. Optical amplification uses the principle of stimulated emission as used in a laser. The three basic types of amplifiers are erbium-doped fiber amplifiers (EDFAs), semiconductor optical amplifiers (SOAs), and Raman amplifiers. The Erbium-Doped Fiber Amplifier (EDFA) is the most commonly deployed OA.

The key performance parameters of optical amplifiers are gain, gain flatness, noise level, and output power. The target parameters when selecting an EDFA, however, are low noise and flat gain. Gain should be flat because all signals must be amplified uniformly. Although the signal gain provided by the EDFA technology is inherently wavelength-dependent, it can be corrected with gain flattening filters. Such filters are often built into modern EDFAs. Low noise is a requirement because noise, along with the signal, is amplified. Because this effect is cumulative and cannot be filtered out, the signal-to-noise ratio is an ultimate limiting factor in the number of amplifiers that can be concatenated. This limits the length of a single fiber link.

2.3.3 Optical Transmitter and Receivers

Light emitters and light detectors are active devices at opposite ends of an optical transmission system. Light emitters, are transmit-side devices that convert electrical signals to light pulses. This conversion is accomplished by externally modulating a continuous wave of light based on the input signal, or by using a device that can generate modulated light directly. Light detectors perform the opposite function of light emitters. They are receive-side opto-electronic devices that convert light pulses into electrical signals.

The light source used in the design of a system is an important consideration because it can be one of the most costly elements. Its characteristics are often a strong limiting factor in the final performance of the optical link. Light-emitting devices used in optical transmission must be compact, monochromatic, stable, and long lasting. Two general types of light-emitting devices are used in optical transmission: light-emitting diodes (LEDs) and laser diodes or semiconductor lasers. LEDs are relatively slow devices, suitable for use at speeds of less than 1 Gbps. Narrow spectrum tunable lasers are available, but their tuning range is limited to approximately 100–200 GHz. Wider spectrum tunable lasers, which will be important in dynamically switched optical networks, are under development.

On the receive end, it is necessary to recover the signals transmitted on different wavelengths over the fiber. This is done using a device called the photodetector. As tunable transmitters, there are also tunable receivers available on the market.

2.3.4 Wavelength Converters

Wavelength converters are devices that convert the incoming signal of a particular wavelength into a signal containing the same information but on a different wavelength. It is possible that an incoming call cannot be accepted in a portion of a network on a particular wavelength because that wavelength is already busy or because other components that work in this wavelength range are not available. In such situations, the data using the incoming wavelength can be switched onto an idle, available wavelength to accommodate the call. Wavelength conversion thus enables efficient spatial reuse of wavelength resources in the network, adding to the flexibility of multi-wavelength systems.

2.3.5 Optical Switches

Most current networks employ electronic processing and use the optical fiber only as a transmission medium. Switching and processing of data are performed by converting an optical signal back to its equivalent electronic form. Such a network relies on electronic switches. These switches provide a high degree of flexibility in terms of switching and routing functions; however, the speed of electronics is unable to match the high bandwidth of an optical fiber. Also, an electro-optic conversion at an intermediate node in the network introduces extra delay. These factors have motivated an attempt towards the development of all-optical networks in which optical switching components are able to switch high bandwidth optical data streams without electro-optic conversion. In a class of switching devices currently being developed, the control of the switching function is performed electronically with the optical stream being transparently routed from a given input of the switch to a given output. Such transparent switching allows for the switch to be independent of the data rate and format of the optical signals.

The simplest optical switch is a fiber cross-connect element that routes optical signals from input ports to output ports. It can be considered as the building block of larger optical switches.

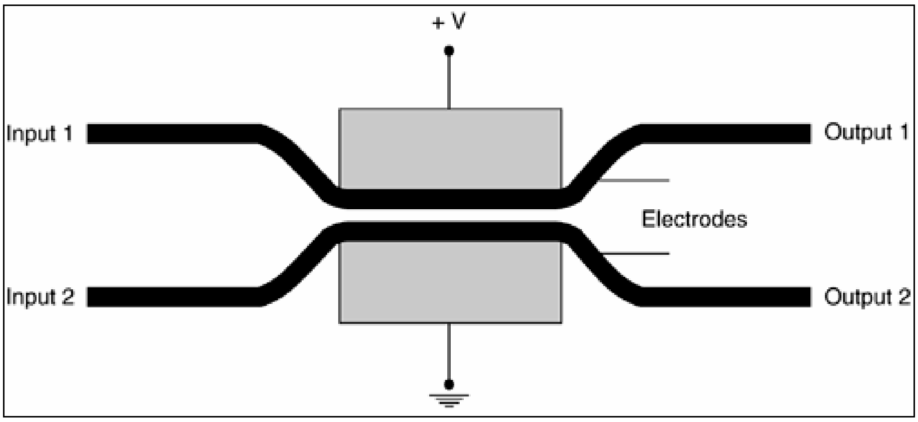

Figure 2.4: A Simple 2 × 2 Switch (Coupler)

The basic cross-connect element in Figure 2.4 is the 2 × 2 crosspoint element. A 2 × 2 crosspoint element switches optical signals from two input ports to two output ports and has two states: cross state and bar state. In the cross state, the signal from input port 1 is routed to output port 2, and the signal from input port 2 is routed to output port 1. In the bar state, the signal from input port 1 is routed to output port 1, and the signal from input port 2 is routed to output port 2.

Optical switches can also be considered as wavelength routing devices. A wavelength routing device can route signals arriving at different input ports of the device to different output ports according to wavelengths of the signals. This accomplished by demultiplexing the different wavelengths from each input port and optionally switching each wavelength separately and then multiplexing wavelengths at each output ports.

A wavelength routing device can be either non-reconfigurable or reconfigurable. A non-reconfigurable router contains no switching stage between demultiplexers and multiplexer. Thus, the routes for different incoming signals are fixed. A reconfigurable switch (also a reconfigurable wavelength routing device) in Figure 2.5 has electronically controlled switches among demultiplexers and multiplexers. In Figure 2.5, the wavelength routing switch has P incoming and outgoing fibers. On each incoming fiber, there are M wavelength channels. The outputs of the demultiplexers are directed to an array of M PxP optical switches between the demultiplexer and the multiplexer stages.

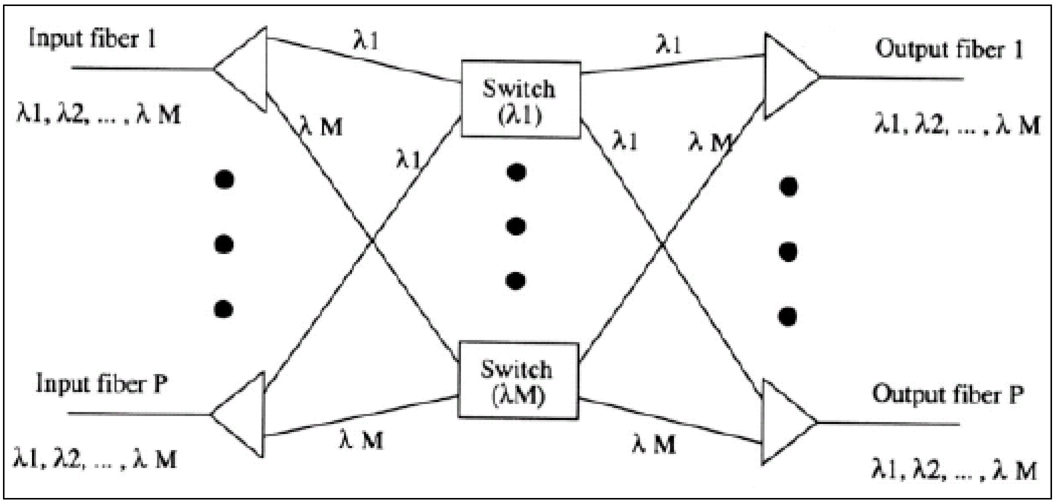

Figure 2.5: A P × P Reconfigurable Wavelength-Routing Switch With M Wavelengths

All signals on a given wavelength are directed to the same switch and then directed to multiplexers associated with the output ports. Finally, multiple WDM channels are multiplexed before directed to output ports.

Research, development, and commercialization of photonic switches encompasses a variety of switching technologies, including opto-mechanical, electro-optic, acousto-optic, thermal, micro-mechanical, liquid crystal, and semiconductor switch technologies **(Mouftah & Elmirghani, 1998)**, **(Hinton, 1993)**.

In order to appreciate the relative merits and shortcomings of different switching technologies, it is important to understand the different metrics used to characterize the performance of a photonic switch fabric. With an ideal photonic switch, all the optical power applied at any input port can be completely transferred to any output port, that is, the switch has zero insertion loss. Also, the optical power does not leak from any input port to any other input port or any undesired output port, that is, it has infinite directivity and zero cross talk. In addition, switch connections can be reconfigured instantaneously, that is, the switching time is zero, and any new connection can be made without rearranging existing connections, that is, the switch is nonblocking. Unfortunately, no switch is ideal, and in practice characteristics of photonic switch elements summarized above affect their performance.

In the following several different switching technologies are introduced. Specifically, the basic principles of switching under different technologies are described and the intrinsic performance limitations and possible reliability concerns are discussed.

2.3.5.1 Opto-Mechanical Switches

This broad category of optical switching technology can be identified based on the use of motion to realize optical switching. They typically have very low loss, and extremely low cross talk. Switching speed of these switches vary from tens of milliseconds to hundreds of milliseconds. Opto-mechanical switches are the most commonly used optical switches today.

The most popular opto-mechanical switches are based on Micro-Electro-Mechanical Systems (MEMS). MEM is a small device that has both electrical and mechanical components. It is fabricated using the tools of the semiconductor manufacturing industry: thin film deposition, photolithography, and selective etching. Frequently, MEMS devices involve the use of semiconductor materials, such as silicon wafers, as well. MEMS devices offer the possibility of reducing the size, cost, and switching time of optical switches, and the ability to manufacture large arrays and complex networks of switching elements.

The switching element in a MEMS optical switch can be a moving fiber, or a moving optical component such as a mirror, lens, prism, or waveguide. The actuation principle for moving the switching element is typically electromagnetism, electrostatic attraction, or thermal expansion. One of the most popular forms of MEMS switches is based on arrays of tiny tilting mirrors, which are either two-dimensional (2D) or three-dimensional (3D).

With 3D arrays in Figure 2.6, the mirrors can be tilted in any direction. The arrays are typically arranged in pairs, facing each other and at an angle of 90 degrees to each other. Incoming light is directed onto a mirror in the first array that deflects it onto a predetermined mirror in the second array. This in turn deflects the light to the predetermined output port. The position of the mirrors has to be controlled very precisely, for example, to millionths of degrees.

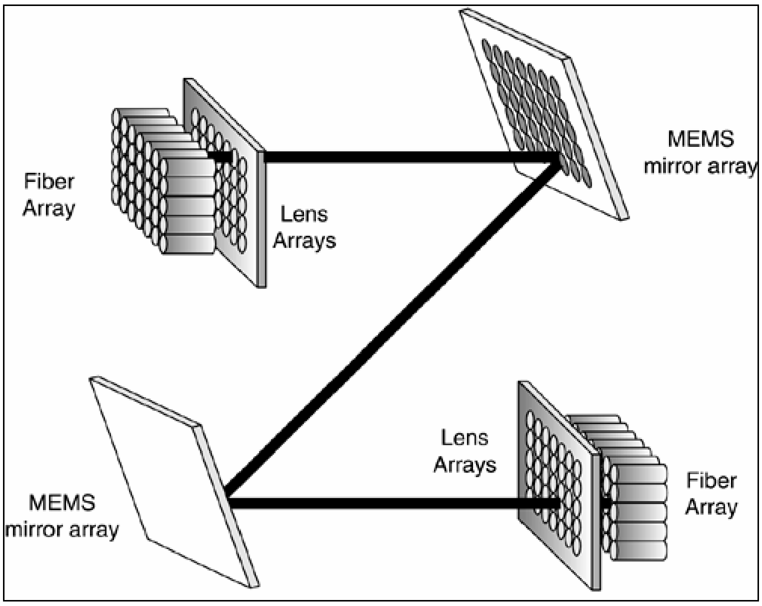

Figure 2.6: 3D MEMS Switch Fabric

2.3.5.2 Electro-Optic Switches

Electro-optic switches are based on directional couplers. A 2 x 2 coupler consists of two input ports and two output ports, as shown in Figure 2.4. It takes a fraction of the power, α, from input 1 and places it on output 1. The remaining power, 1-α, is placed on output 2. Similarly, a fraction, 1-α of the power from input 2 is distributed to output 1 and the remaining power to output 2. A 2 x 2 coupler can be used as a 2 x 2 switch by changing the coupling ratio α. In electro-optic switches, the coupling ratio is changed by changing the refractive index of the material in the coupling region. One commonly used material for this purpose is lithium niobate ($LiNbO_3$). Switching is performed by applying the appropriate voltage to the electrodes. Electro-optic switches tend to be fast with switching times in the nanosecond range. Since the electro-optic effect is sensitive to polarization, electro-optic switches are inherently polarization sensitive, and tend to have relatively high loss.

2.3.5.3 Acousto-Optic Switches

In an acousto-optic device, a light beam interacts with traveling acoustic waves in a transparent material such as glass. Acoustic waves are generated with a transducer that converts electromagnetic signals into mechanical vibrations. The spatially periodic density variations in the material, corresponding to compressions and rarefactions of the traveling acoustic wave, are accompanied by corresponding changes in the medium's index of refraction. These periodic refractive index variations diffract light. Sufficiently powerful acoustic waves can diffract most of the incident light and therefore deflect it from its incident direction, thus creating an optical switching device. Acousto-optic switches are wavelength dependent and are more suitable for wavelength selective switches.

2.3.5.4 Thermo-Optic Switches

These switches are based on Mach-Zehnder interferometers **(Green, 1992)**, **(Ramaswamy & Sivarajan, 2001)**. A Mach-Zehnder interferometer is constructed out of two directional couplers interconnected through two paths of differing lengths as shown in Figure 2.7. By varying the refractive index in one arm of the interferometer, the relative phase difference between two arms can be changed, resulting in switching an input signal from one input port to another. These switches are called thermo-optic switches because the change in the refractive index is thermally induced. Thermo-optic switches suffer from poor cross talk performance and are relatively slow in terms of switching speed.

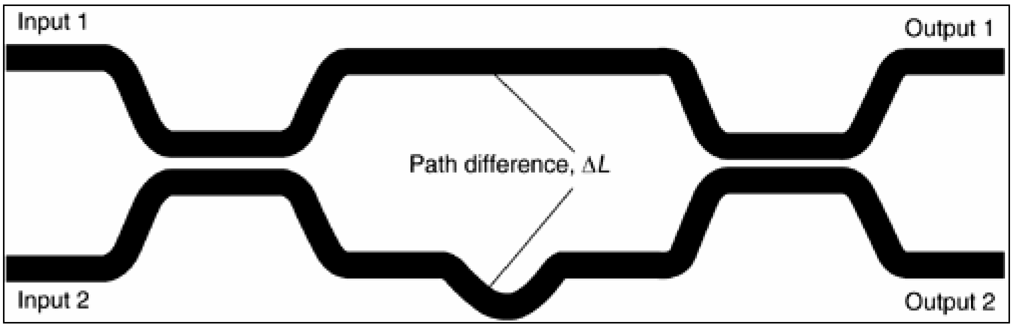

Figure 2.7: Mach-Zehnder Interferometer

2.3.5.5 Magneto-Optic Switches

The magneto-optic effect refers to a phenomenon in which an electromagnetic wave interacts with a magnetic field. The Faraday Effect is an important magneto-optic effect whereby the plane of polarization of an optical signal is rotated under the influence of a magnetic field. Magneto-optic switches use Faraday Effect to switch optical signal. These switches are typically characterized with low loss and slow switching speed. They are somewhat wavelength dependent.

2.3.5.6 Liquid Crystal Optical Switches

A liquid crystal is a phase between solid and liquid. Liquid crystal-based optical switches also utilize polarization diversity and polarization rotation to achieve optical switching. Switches of this type are typically quite wavelength dependent, since the amount of polarization rotation depends on wavelength. Liquid crystal polarization rotation is also intrinsically temperature dependent. Switching speed is relatively slow, usually between 10–30 ms range, since the switching mechanism requires reorientation of rather large molecules.

2.4 Terminology of Optical Networks

This section introduces basic terminology about wide area optical networks, such as lightpath, routing and wavelength assignment, virtual topology design and reconfiguration.

2.4.1 Lightpath

Wide area optical networks are composed of nodes that employ optical cross-connects (OXCs) and WDM channels called lightpaths that are established between node pairs. A lightpath is an optical channel between two nodes. The traffic on a lightpath does not get converted into electronic format at any intermediate node it passes and is routed as an optical signal throughout the physical topology. Each intermediate node provides a wavelength routing optical bypass capability with the help of its installed OXC to support lightpath. With wavelength continuity constraint, the lightpath becomes a sequence of physical links forming a path from source to destination, along with a single wavelength. Lightpaths logically connects two distinct nodes even if they are not directly connected in the physical topology. Traffic demands among nodes can be provisioned by using the established lightpaths. A lightpath consumes a transmitter at its start node, a receiver at its end node and one available wavelength at each physical link it spans. Since transceivers on nodes and number of wavelengths on physical links are limited, only a limited number of lightpath can be set up over a physical topology.

2.4.2 Routing and Wavelength Assignment (RWA)

Once a set of lightpaths is determined, routing of each lightpath and assignment of wavelength to each is required. This is a resource reservation issue called as routing and wavelength assignment problem. In RWA problem, a set of lightpaths that need to be setup on the network and a constraint on the number of wavelengths is given. The goal is to identify the routes over which the lightpaths should be established and determine wavelengths which should be assigned to these lightpaths. Lightpaths are said to be blocked when they could not set up due to constraints on routes and wavelengths. RWA is an optimization problem which tries to minimize this blocking probability.

A lightpath may have one or more wavelengths through all fiber links it spans. The lightpath is said to satisfy the wavelength continuity constraint if it operates on the same wavelength. Two lightpaths that passes over a common fiber should not be assigned the same wavelength. If a switching node is equipped with a wavelength converter, this removes the wavelength continuity constraint and enables a lightpath switching among various wavelengths on its route.

The RWA problem can be classified either static or dynamic according to the nature of the incoming connection requests. In static lightpath establishment, the set of connection request are known prior to design and the goal is to set up all connections while minimizing the network's resources. On the other hand, a lightpath establishment is triggered with an incoming connection request and released after some amount of time in dynamic lightpath establishment. Static RWA can be formulated as an integer linear program (ILP) whose objective is to minimize the number of lightpaths passing through a fiber link. Since the lightpath requests and physical topology are known previously, the problem is called offline RWA. The general problem is NP-complete, this make it intractable to solve for large networks. Therefore, RWA is divided into subproblems and each subproblem is solved independent of others. RWA problem is divided into two subproblems of routing and wavelength assignment each. Once the routing subproblem is solved for a connection request, a wavelength assignment routine (can be reduced to graph coloring) is applied to derive the optimal solution. In dynamic RWA problem, linear program is not applicable. Thus, heuristic methods are proposed to solve previously defined subproblems. Fixed routing, fixed alternate routing, adaptive routing are the basic routing heuristics used for the solution of routing subproblem. Random, first-fit, least used, most used, min product, least loaded heuristics are applied for wavelength assignment subproblem.

2.4.3 Virtual Topology Design (VTD)

A lightpath constructs single-hop communication channel between two arbitrary nodes in a physical topology. Since a physical topology has limited number of wavelengths, it may be impossible to establish lightpaths between all node pairs. This makes multihopping unavoidable between some nodes. Virtual topology can be defined as a set of lightpaths that carry traffic in optical domain using optical circuit switching and packet forwarding among lightpaths is performed in electronic domain by using electronic packet switching. Figure 2.8 shows a possible virtual topology explaining the concepts summarized above over a physical topology.

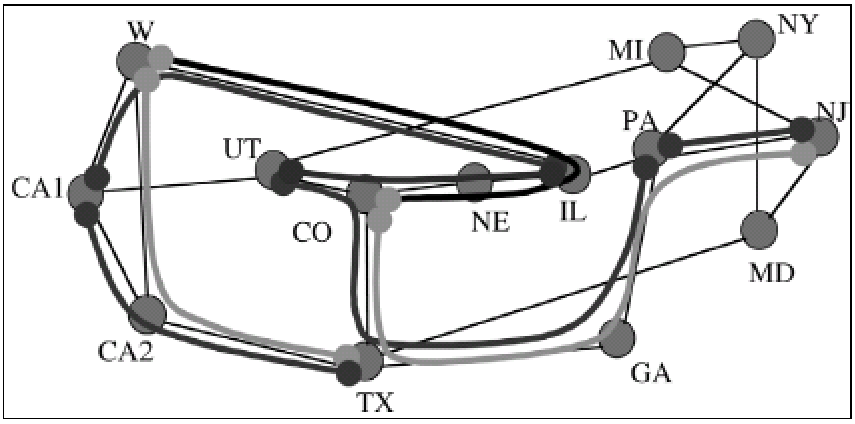

Figure 2.8: A Sample Virtual Topology Over NSFNET Physical Topology

VTD can be thought as an optimization problem whose constraints are;

- Number of transceivers and wavelengths

And possible objectives are;

- Maximization of packet traffic
- Balancing the lightpath loads
- Minimization of network resource utilization

- Minimization of average packet delay

Since the objective functions mentioned above are nonlinear and simpler versions of this problem was shown to be NP-hard, mostly heuristic approaches for the solution of VTD problem is proposed. Virtual topology design problem can be decomposed into four subproblems. These subproblems are as follows;

a. Topology Subproblem: Determine the virtual topology over physical topology. (set of lightpaths in terms of source and destination nodes)

b. Lightpath Routing Subproblem: Determine the physical links that each lightpath spans, this is called routing of the lightpaths over the physical topology

c. Wavelength Assignment Subproblem: Assign a wavelength to each lightpath in the virtual topology so that no violation of wavelength restrictions occurs for each physical link.

d. Traffic Routing Subproblem: Route packet traffic between source and destination nodes over the virtual topology obtained.

Solving the subproblems in sequence and combining the solutions may not construct the optimal solution for whole VTD, but it is certain to obtain the sub-optimal solutions of the decomposed VTD problem.

2.5 Virtual Topology Reconfiguration (VTR)

As stated in 2.4.3 logical topology design is the selection and establishment of a set of lightpaths in an optical network according to a traffic pattern. Most of time, traffic patterns of upper layers may vary and the current logical topology may become inefficient to realize traffic demands of upper layers. Fortunately, there is an advantage of the optical networks that they are able to reconfigure their logical topology to adapt to changing traffic patterns. This flexibility is one of the major advantages of optical networks over classical electronic networks. The reconfiguration process moves the current logical topology to a new one by tearing down and establishing existing and new lightpaths, respectively. The impact of reconfiguration should be carefully considered since packet delays or loses may occur during this process. As a principal, a fast reconfiguration algorithm should achieve smallest reconstruction on virtual topology with lowest degradation to performance.

Virtual topology reconfiguration is another NP-hard problem as previously stated problems in this study. Therefore, there is a tendency to divide VTR problem into smaller subproblems and use heuristics for solutions. There exist two subproblems in reconfiguration;

- **a.** Design the new virtual topology by considering the new traffic pattern
- **b.** Transform from the current virtual topology to the new one with minimal disruption to continuous traffic pattern.

The transformation described in b can be either sudden by destroying all existing lightpaths and establishing all lightpaths in the new virtual topology or step-by-step by making small changes over the existing virtual topology to reach target virtual topology. There is often a trade-off in reconfiguration algorithms between the optimality of new virtual topology and the amount of disruption during reconfiguration transition.

2.5.1 Survey of Reconfiguration Studies

Selected studies about virtual topology reconfiguration are summarized in this title. VTR is composed of recursively complex problems which were stated in previous paragraphs such as VTD and RWA. Reconfiguration studies available in literature still have open problems such as how to reconfigure and when to reconfigure the optical network. Some of open problems arise because of the recursive subproblems, while the others are introduced by the concept of reconfiguration itself. Next of this chapter is devoted to brief summaries of studies performed about virtual topology reconfiguration.

Labourdette et al. (1994) considers the reconfiguration transition problem by introducing an approach where the network reaches some target connectivity graph through a sequence of intermediate connection graphs, so that two successive graphs differ by a single "branch-exchange" operation. The proposed scheme provides a minimally disruptive effect on traffic such that only two links are disrupted with a single transition at any time. Three polynomial time algorithms that search for shortest sequences of branch exchange operations are given in order to minimize the overall reconfiguration time. **Rouskas & Ammar (1995)** presented the reconfiguration phase as a Markovian Decision Process and developed heuristics to obtain good reconfiguration policies in terms of packet loss during reconfiguration. **Bala et al. (1996)** proposed a method for reconfiguration of a WDM optical network to adapt to changing traffic pattern at the ATM layer. Changing traffic patterns resulted in the requirement for changing ATM network topologies that are known before reconfiguration take place. Assuming that the ATM switches access the WDM layer, the proposed method sized the ATM switches and assigned wavelengths between pairs of ports at the switches so as to support the required ATM network topologies in a hitless manner. Also, bounds on the number of wavelengths need to support the introduced reconfiguration scheme were proposed in this study.

Kim et al. (1999) proposed a heuristic algorithm to minimize the number of OXCs required reconfiguring the logical topologies of WDM networks. From the results of several experiments, authors found that not all nodes require OXCs and the number of OXCs depends on the similarity between logical topologies. In **Narula-Tam & Modiano (2000)**, iterative reconfiguration algorithms for load balancing of lightpaths were developed and analyzed. Main purposes of the algorithms are to minimize the maximum link load while tracking the rapid changes in traffic pattern. At each iteration, proposed algorithms make only small changes to the network topology and this leads to minimal disruption to the network. The performance of the algorithms were analyzed under several dynamic traffic scenarios and also shown that large reconfiguration gains are achievable with limited number of wavelengths. **Banerjee & Mukherjee (2000)** introduced a reconfiguration procedure which searches through all possible optimal virtual topologies in order to obtain a solution which shares the maximum number of lightpaths with the previous virtual topology for a changed traffic matrix. This solution to the reconfiguration problem generates a virtual topology which minimizes the amount of switch retunings that need to be performed in order to adapt the virtual topology to the new traffic pattern.

In **Ramamurthy & Ramakrishnan (2000)**, proposed reconfiguration algorithm includes trade-offs between the amount of reconfiguration necessary and average packet delay. The reconfiguration algorithm in this study is independent of the virtual topology design algorithm that used. This gives resilience for using different virtual topology design algorithms with the proposed reconfiguration scheme. The number of reconfiguration steps was used as a useful metric in this study. On the other hand, this paper did not deal with the problem of detecting the need for reconfiguration, i.e. when to trigger reconfiguration. **Narula-Tam et al. (2000)** state that WDM networks will allow multiple virtual topologies to be dynamically established on a given physical topology. Authors determine the number of wavelengths required to support all possible virtual topologies on a bidirectional ring physical topology. First, they determined wavelength requirements for networks using shortest path routing, then by presenting a novel adaptive lightpath routing and wavelength assignment strategy they reduced network wavelength requirements. They also showed that this reduced wavelength requirement is optimal. These results were first derived for the single port per node case and then extended to networks with multiple ports per node. **Baldine & Rouskas (2001)** analyzes the issues arising in the reconfiguration phase of broadcast optical networks. Authors developed and compared reconfiguration policies to determine when to reconfigure the network and presented an approach to carry out the network transition by describing a class of strategies that determine how to retune the optical transceivers. The problem whose objectives were identified as the degree of load balancing and the number of retunings were formulated as a Markovian Desicion Process. Consequently, they developed a system which enables the selection of rewards and costs that can be used to achieve the desired balance among various performance criteria. The results obtained from this study are applicable to networks of large size.

In **Alfouzan & Jayasumana (2001)** a reconfiguration algorithm was proposed both in order to balance the traffic loads among wavelength channels and minimize the number of retunings. The proposed algorithm was proved to have significant advantage over the existing reconfiguration schemes in the paper. **Qin et al. (2002)** described an algorithm based on simulated annealing for solving the joint logical topology design and routing problem for WDM optical networks with the objective of minimizing the maximum utilization of any link. Authors' main contribution is to introduce a novel mechanism to accelerate the running speed of the simulated annealing algorithm. **Liu et al. (2002)** presented three "one-hop traffic maximization"-oriented heuristic algorithms for lightpath topology design, and one heuristic algorithm for reconfiguration migration. These algorithms aim at guaranteed connectivity and take full advantage of available physical resources to accommodate maximum future growth of traffic demands. Furthermore, the algorithms aim at operational issues such as supporting ongoing services. To verify the performance of the presented reconfiguration algorithms, authors have conducted a simulation study. The simulation results showed that the reconfiguration algorithms provide higher network throughput and reduced average hop distance over the fixed topology. Based on the framework and the developed algorithms, authors have set up an IP over WDM network testbed and developed a traffic engineering system prototype based on the GMPLS framework leveraging on WDM network reconfigurability.

Yang & Ramamurthy (2002) proposed an analytical model to study the impact of virtual topology reconfiguration on optical networks. The introduced model identified and analyzed the impact factors from both the data and control planes independent of any specific VTR algorithm or policy. This allows the carriers choose a VTR algorithm or policy according to the real time network situations. A uniform cost model was derived from these factors, and provided a practical and precise criterion for carries to compare different VTR algorithms to decide for triggering VTR operations. **Zheng et al. (2004)** studied the virtual topology design and reconfiguration problem of VPN over all-optical WDM networks. VPN requires a set of lightpaths to be established over physical WDM topology to meet the traffic demands and also needs a dynamic reconfiguration of lightpaths with its changing traffic characteristics. First, the integer linear program formulation of the problem was presented with minimizing the multiobjectives such as average propagation delay over a lightpath, maximum link load, and reconfiguration cost. The purpose was to improve the performance and meet the service requirements of VPNs. Since the given formulation was NP hard to solve, a genetic algorithm based method was proposed to obtain the optimal solutions. For a tractable solution, the proposed algorithm was divided into two independent stages: route computing and path routing. This algorithm provided optimal solutions in its earlier stages. In **Stosic & Spasenovski (2003)**, a practical model for reconfiguration of virtual topology in SDH/WDM networks was presented. The model minimizes the difference between initial and reconfigured network. Furthermore, under these conditions it minimizes the average hop distance of routed traffic.

Gençata & Mukherjee (2003) proposes an adaptation mechanism to follow the changes in traffic without a priori knowledge of the future traffic pattern. By this aspect this work differs from others which redesign the virtual topology according to an expected traffic pattern. The main idea of this study is based on the continuous measurement of traffic loads on each lightpaths in order to adapt the underlying optical connectivity. This adaptation mechanism includes adding or deleting one or more lightpath at a time. Some parameters are introduced to evaluate the utilization of lightpaths and trigger an adaptation step. **Sreenath & Murthy (2002)** proposed four heuristic algorithms for online reconfiguration of WDM optical networks. The performance of these heuristic algorithms was compared in terms of objective function value of reconfigured topology, number of changes made in the existing topology to get the reconfigured topology, and the time required to compute the changes in the existing topology. **Mohan et al. (2003)** presents a reconfiguration algorithm which is based on the concept of splitting and merging existing lightpaths to reduce the virtual topology reconfiguration cost in WDM optical ring networks. The objective of the proposed algorithm is to design a new virtual topology so as to minimize the number of changes that need to be made in the current virtual topology while keeping the network congestion as small as possible. Algorithm in this study, allows only a few lightpath changes at each step of the reconfiguration procedure.

Lee et al. (2003) formulated the optimal reconfiguration policy as a multi-stage decision-making problem to maximize the expected reward and cost function over an infinite horizon. To counter the continual approximation problem brought by heuristic approach, they take the traffic prediction into consideration. They further propose a new heuristic reconfiguration scheme to realize the optimal reconfiguration policy based on predicted traffic. Simulation results showed that proposed scheme overtakes the reconfiguration strategy considering traffic without prediction. **Golab & Boutaba (2004)** concerns the problem of automatically updating the configuration of an optical network to accommodate changes in traffic demand, which entails making a reconfiguration policy decision, selecting a new configuration, and migrating from the current to the new configuration. Existing solutions were classified according to their algorithmic properties, and compared on the basis of performance, computational cost, and flexibility. **Prathombutr et al. (2004)** proposed a model for a series of reconfigurations in wavelength-routed optical network. The model contains two tasks: a reconfiguration process and a policy. The reconfiguration process generates the Pareto front or a set of nondominated solutions that determines two competitive objectives in the reconfiguration problem simultaneously by using the concept of Pareto Optimal. The policy picks one of the solutions in the Pareto front that generates the optimal outcome by using the concept of Markov Decision Process.

Xu et al. (2004) presented a new simulated annealing algorithm to resolve the logical topology reconfiguration problem in IP over WDM networks. From performance comparisons, they have shown that with the new SA algorithm, ideal solution can be found especially for a bigger size network. Also by introducing the threshold on congestion, the optimal congestion requirement and operation complexity can be balanced by tuning this threshold to a feasible value. For an effective solution discovery, a two-stage SA algorithm was developed for multiple objectives optimization. **Koçak et al. (2004)** proposed a heuristic in this paper deletes unnecessary loaded lightpaths and adds lightpaths to decrease the load in the other lightpaths. By this way, traffic weighted average distance of the network and the maximally loaded lightpath's load can be decreased; load balancing can be achieved. **Zhang et al. (2005)** introduces several heuristic algorithms that move the current logical topology efficiently to the given target logical topology in large-scale wavelength-routed optical networks. In the proposed algorithms, the performance improvement/degradation of data transmission caused by a new lightpath is considered as benefit for establishing the new lightpath. The proposed algorithms construct the new logical topology starting from a lightpath with the largest benefit to the user traffic.

In **Gillani et al. (2005)**, a new approach of adaptive reconfiguration under dynamic traffic conditions for long haul networks was proposed. Two auxiliary heuristic algorithms were introduced to support the proposed reconfiguration approach. One of them makes the decision making for network reconfiguration while the second is given to derive the new logical topology from the previous one by lightpath additions or deletions. The performance evaluation of the proposed algorithm was tested and its advantages were shown. **Sumathi & Vanathi (2005)** presented a virtual topology reconfiguration heuristic to minimize the congestion in the network thereby balancing the network load for various percentage of traffic change. **Bhandari & Park (2005)** modeled the reconfiguration problem of mesh optical networks as MILP, where authors tried to minimize network disruption and hop length. They minimized network disruption by minimizing the transceiver retuning needed at each optical node. Then they proposed a heuristic algorithm which tries to minimize network disruption and then minimize hop length whenever possible.

Yeh et al. (2005) studied the virtual topology reconfiguration problem in the networks using MG-OXC architecture. Authors assumed that the future traffic pattern was known a priori and reconfigured the original topology, without dramatically changing the current virtual topology, to the new one that was suitable for the new traffic pattern. They proposed a heuristic algorithm to solve the problem by constructing an auxiliary graph to help determining the addition, deletion, or keeping of the virtual links. **Sinha & Murthy (2005)** proposed a framework for the reconfiguration in the network according to the changes in the traffic. It collects the traffic changes in the network and reconfigures the network depending on the current reconfiguration policy, and also updates the reconfiguration policy whenever required. The framework uses an algorithm for sequential prediction of future traffic sequences. Prediction of traffic sequences and the cost incurred in re determining the reconfiguration policy were quantified from an information theoretic point of view. Simulation results demonstrated the effectiveness of the proposed framework compared with the fully predictable scheme and totally unpredictable scheme. **Saad & Luo (2005)** addressed the problem of selecting the new virtual topology that, upon changing traffic patterns, maximizes the carried traffic of connections, while guaranteeing that ongoing connections are not disrupted. A heuristic reconfiguration algorithm that is based on partitioning the traffic demands, so as to maintain wavelength loads as balanced as possible, followed by solving a sequence of single-wavelength subproblems was also introduced.

Takagi et al. (2006) proposes several heuristic algorithms that reconfigure logical topologies in wide-area wavelength routed optical networks. Reconfiguration algorithms attempt to control the disruption to the network as small as possible during the reconfiguration process. For this purpose, a lightpath is taken as the minimum reconfiguration unit. The results showed that very simple algorithms provide very small computational complexity but poor performance and an efficient algorithm provides reasonable computational complexity with very good performance. More complex algorithms may improve performance somewhat further but have unrealistically large computational complexity. In **Din (2007)**, virtual topology configuration transition problem (WVTCTP) which minimizes the average weighted hop distance was studied. Since the WVTCTP is NP-hard, a genetic algorithm (GA) was proposed to solve it. Simulated results showed that the proposed GA can get better performance than heuristics, simulated annealing, and iterative improving methods. **Tak et al. (2007)** proposes a reconfiguration approach adapting multiobjective optimization in WDM optical networks. The reconfiguration problem in WDM optical networks requires a process of multi-objective optimization because the objective of reconfiguration considers the network performance and the network cost simultaneously. Number of lightpath routing changes is exploited for the measurement of network cost. The proposed reconfiguration technique considers a reconfiguration process and a reconfiguration policy. The reconfiguration process finds a set of non-dominated solutions and the reconfiguration policy picks a solution from the set of non-dominated solutions.

3 THE FRAMEWORK USED IN THE SIMULATIONS

The goal of this thesis is to study the effects of reconfiguration in optical domain to the upper layers carrying network traffic. In order to perform this study, an IP simulation environment that operates ignorant of the underlying topology was developed. Main function of this IP layer will be producing and transmitting IP packets according to the incoming traffic connection requests regardless of lower level physical architecture. This chapter first gives a brief summary of Internet Protocol then describes Fishnet based framework which will be used in the simulations of implemented reconfiguration algorithms. Then, modifications over the framework will be presented.

3.1 Internet Protocol

The Internet Protocol (IP) is a data-oriented protocol used for communicating data across a packet-switched network. IP is a network layer protocol in the internet protocol suite and is encapsulated in a data link layer protocol (e.g., Ethernet). As a lower layer protocol, IP provides the service of communicable unique global addressing amongst computers.

Data from an upper layer protocol is encapsulated inside one or more packets/datagrams. No circuit setup is needed before a host tries to send packets to a host it has previously not communicated with, thus IP is a connectionless protocol. This is quite unlike Public Switched Telephone Networks that require the setup of a circuit before a phone call may go through (a connection-oriented protocol).

Because of the abstraction provided by encapsulation, IP can be used over a heterogeneous network (i.e., a network connecting two computers can be any mix of Ethernet, ATM, FDDI, Wi-fi, token ring, etc.) and it makes no difference to the upper layer protocols. Each data link layer can (and does) have its own method of addressing (or possibly the complete lack of it), with a corresponding need to resolve

IP addresses to data link addresses. This address resolution is handled by the Address Resolution Protocol (ARP).

IP provides an unreliable service (i.e., best effort delivery). This means that the network makes no guarantees about the packet and none, some, or all of the following may apply:

- data corruption
- out of order (packet A may be sent before packet B, but B can arrive before A)
- duplicate arrival
- lost or dropped/discarded

In terms of reliability the only thing IP does is ensure the IP packet's header is error-free through the use of a checksum. This has the side-effect of discarding packets with bad headers, and with no required notification to either source or destination by sending an ICMP message. To address any of these reliability issues, an upper layer protocol must handle it. For example, to ensure in-order delivery the upper layer may have to cache data until it can be passed up in order. If the upper layer protocol does not control its own size, and sends the IP layer too much data, IP is forced to fragment the original datagram into smaller fragments for transmission. IP provides re-ordering of any fragments that arrive out of order by using the fragmentation flags and offset. TCP is a good example of a protocol that will adjust its segment size to be smaller than the MTU. User Datagram Protocol (UDP) and Internet Control Message Protocol (ICMP) are examples of protocols that disregard MTU size thus forcing IP to fragment oversized datagrams. The primary reason for the lack of reliability is to reduce the complexity of routers.

Perhaps the most complex aspects of IP are IP addressing and routing. Addressing refers to how end hosts become assigned IP addresses and how subnetworks of IP host addresses are divided and grouped together. IP routing is performed by all hosts, but most importantly by internetwork routers, which typically use either interior gateway protocols (IGPs) or external gateway protocols (EGPs) to help make IP datagram forwarding decisions across IP connected networks.

3.2 The Framework: Fishnet Project

Fishnet is a software project developed at the University of Washington for teaching the core principles of network protocol design and implementation. The current version is written primarily in Java, with supporting scripts in Perl and Ruby. The implementation was changed from Ruby to Java since; Java has the advantage of being strongly typed and very well documented. The set of instructions for installing, compiling, and running Fishnet for the first time can be found at **(Gribble, 2005)**.

3.2.1 Fishnet Architecture

The Fishnet infrastructure is an environment for the development of network protocol stacks. Conceptually, each node represents a computer having its own network stack. Pairs of nodes are connected to each other by links; each link has a latency, bandwidth, and loss rate.

There are about two different models for implementing a network stack: the process-per-protocol model and the process-per-message model. Fishnet uses yet a third model: an event-driven architecture, in which your code must completely process each packet before it can deal with the next one. This means there is no need to worry about concurrent processing of multiple packets. To deliver packets, the Fishnet infrastructure must be able to call your code using upcalls. To make this possible, your code will need to implement methods for functions such as receiving a packet or receiving keyboard input, and register callbacks with the infrastructure so that it knows what method to call when certain other events occur.

Fishnet performs simulation by reading a simulation file. A sample simulation file is given in Figure 3.1. Simulation file commands are case sensitive. Special attention must be paid on the spaces. Commands are parsed by using the spaces as delimiters thus it is very important to put spaces where required. Also putting consecutive spaces will cause the command to be incorrect.

The topology file is line-oriented (one command per line). Nodes (e.g., a, b) are referred to by their Fishnet Address (0…254). Fishnet supports up to 255 nodes. Command between [] means optional while <> means “type” specified inside <>.

```
edge 0 1
edge 1 2
edge 2 3
edge 3 4
edge 0 4
time + 5000
1 4 Ping before failing node 0
time + 20000
echo ------- Failing node 0 ---------
fail 0
time + 50000
1 4 Ping after failing node 0
time + 20000
echo ------- Restarting node 0 ---------
restart 0
time + 50000
1 4 Ping after restarting node 0
time + 25000
exit
```

Figure 3.1: A Sample Simulation File

Comments:

[// | #] <comment>: any line starting with // or # is ignored

Define an edge:

edge a b [lossRate <double>] [delay <long>] [bw <int>]: this creates an edge between a and b, with the specified loss rate, delay (in milliseconds), and bw (in KB/s), or changes the specifics for an existing link, defaults are 0 lossRate, 1 msec delay, and 10Kb/s bw

Putting delays into simulation:

time [+]x: any subsequent command is delayed until simulation/real has reached x (or now + x, if + is used), in milliseconds from start. If + is used there must be a space between + and x.

Removal of a node or an edge:

fail a [b]: this removes node a (if b is not specified) or an edge (if it is)

Restarting a node or an edge:

restart a [b]: this restarts a node or edge. Previous information about the node/edge is preserved

Send message between nodes:

a b <msg>: a delivers text <msg> to node b

Printing text:

echo text: prints the text

Stop simulation:

exit: cleanly stop the simulation run

3.2.2 Fishnet Classes

Fishnet project has many classes to carry out the transmission of IP packets. Most important of them are listed in the following.

- Node: Implements the protocol stack for a single Fishnet node. It uses methods defined in the Manager abstract class to talk to the simulated network.
- Manager: The abstract class that provides Node with an interface for communicating with the network and setting timers.
- Simulator: Manages a simulation. All nodes are instantiated and simulation is controlled by this class.
- Packet: Defines headers for a packet sent across the network. It provides methods to pack and unpack itself which is also known as marshalling and unmarshalling respectively.
- LinkState: Defines the headers for a link state advertisement.
- Protocol: Defines the protocols recognized by Fishnet.
- Callback: Provides a mechanism for registering callbacks in Java.
- Utility: Provides some useful general-purpose functions. In particular, there are two methods that convert Strings to byte arrays, and vice versa, using ASCII encoding.

3.3 Modifications over Fishnet

All modifications over Fishnet were performed without violating its event-driven simulation structure. Added functions are implemented in a way that they can easily be added to existing event queue and can be invoked when the timestamp assigned each of them equals to the current time. Physical topology construction, virtual topology construction, virtual topology reconfiguration, traffic generation, packet sending, packet receiving, and parsing of simulation file are among the most important events used throughout the simulation cycle.

Fishnet nodes are not capable of routing a connection request through network. The main contribution added to Fishnet is link state routing capability **Tanenbaum (2002)** used in IP layer. A node must implement link state routing to construct a routing table, and use this routing table to forward packets towards their destination. A link-state protocol generally involves four steps:

- Neighbor discovery: When a router is booted its first task is to learn who its neighbors are. It accomplishes this goal by sending a special PING packet on each point to point line. The router on the other end is expected to receive this PING packet and build a link state packet containing all neighbors' info.
- Link State Flooding: The trickiest part of the algorithm is distributing the link state packets reliably. The fundamental idea is to use flooding periodically to distribute the link state packets. To keep the flood in check, each packet contains a sequence number that is incremented for each new packet sent. Routes keep track of all the (source router, sequence) pairs they see. When a new link state packet comes in, it is checked against the list of packets already seen. If it is new, it is forwarded on all lines. If it is a duplicate, it is discarded. If a packet with sequence number lower than the highest one seen so far arrives, it is rejected as being obsolete since the router has more recent data.
- Shortest-path calculation: Once a router has accumulated a full set of link state packets, it can construct the entire subnet graph because every link is represented. Now Dijkstra's algorithm can be run locally on each node to

construct the shortest path to all possible destinations. The results of this algorithm can be installed in the routing tables. For a subnet with n router, each of which has k neighbors, the memory required to store the input data is proportional to kn. For large subnets, this can be a problem.

- Forwarding: Now the fishnet node should forward packets using the next-hop neighbors in calculated routing table. The exception is packets that have the broadcast address as their destination (e.g., link state packets); these should continue to be flooded. Note, then, that when your node receives a packet, it may perform one of three actions: (1) if the packet is destined for the node, it will "deliver" the packet locally; (2) if the packet is destined for another node, it will "route" the packet; (3) if the packet is destined for the broadcast address, it will both deliver packet locally, and continue flooding the packet, subject to the TTL and duplicate-avoiding constraints.

As seen in Figure 3.1, basic Fishnet supports traffic requests based on individual packet transmission. In this study, traffic requests are not given in packet by packet. Instead, a more general and applicable method for traffic requests will be used in simulations. Average traffic rates between network nodes are represented as a traffic matrix. The packet traffic is created by a packet traffic generator considering traffic matrix. For this purpose, a Poisson Traffic generator is implemented and added to Fishnet code. “traffic” command was defined to generate Poisson traffic among the nodes of the virtual topology. The basic usage of traffic command is given as follows,

traffic traffic_file time : the traffic matrix given in “traffic_file” is applied to virtual topology for “time” milliseconds.

To show the ability of reconfiguration, the topology over which Fishnet operates is divided to physical and virtual topologies. Undermost layer (named physical topology layer) is equipped with optical switches as nodes and high capacity fiber links as edges. A rearrangeable virtual topology layer is placed over the top of the underlying physical topology layer. The rearrangement of the upper virtual topology layer is performed with the help of optical switches at nodes and wavelengths at fiber links among the nodes. Virtual topology design and reconfiguration algorithms are added to Fishnet to derive the appropriate virtual topology over which the IP packet traffic will be routed. For this purpose, a new command named "vt" for generation and reconfiguration of a virtual topology is added to the project. The basic usage of vt command is;

vt traffic_file: determine the new virtual topology according to the traffic matrix given in "traffic_file".

Modification over Fishnet was performed by implementing and updating/adding the following classes.

- AuxArc: Represents the edges of auxiliary graph constructed in Branch-Exchange algorithm proposed in section 4.2.4
- AuxEdge: Contains the edge information that shows conflict relations of old and new lightpaths in MDPF algorithm given in section 4.2.3
- AuxGraph: Represents the auxiliary graph employed in Branch-Exchange algorithm. AuxGraph has methods that perform construction and validation of matrices used by BE and a Dijsktra implementation which is used to find maximum number of vertex disjoint cycles in the auxiliary graph.
- AuxNode: Represents node structure used in Auxiliary graph employed in BE algorithm.
- CommandsParser: This is the base class of SimulationCommandsParser class and contains methods for parsing simulation file. CommandsParser class is available in basic Fishnet architecture. Modifications on parse of edge command for generation of optical layer, parse of traffic and vt commands are implemented as methods in this base class and its subclass SimulationCommandsParser together.
- Dijkstra: This class is used by each node in the network for evaluation of routing tables. It performs calculation of shortest paths (by using delays) to all other nodes in the network and construction of routing tables.

- ForwardPkt: Contains information such as source address, sequence number, protocol and time of forwarding of a packet for monitoring the status of a control or data packet during its transmission across the network.

- LightpathRoute: Contains information about an established lightpath such as wavelength, transceivers and route. This class is used to store the status of a lightpath and represents each lightpath of a virtual topology.

- MDPF: Implements MDPF algorithm given in section 4.2.3. MDPF has methods that deals with construction of auxiliary graph, removes old and new conflicting lightpaths, adds conflict relations to the auxiliary graph, and performs reconfiguration transition by constructing each new lightpath periodically.

- NextPacket: Holds the necessary parameters for generation of new packets and mainly used by TrafficGenerator class. NextPacket class has parameters such as source, destination, time, size, inter arrival time, and mean traffic rates for packet generation.

- Node: This class is already in Fishnet project but many new methods are added in this study. Various methods for packet generation, timeout detection of control packets, management of physical topology (use, free and check availability of optical resources), neighbor discovery, routing table construction, routing table lookup, packet receipt, and packet send are implemented and added. Furthermore, important data members such as active neighbors, forwarded control packet's list, link state tables, routing tables, physical resources (transceiver, wavelengths) and performance evaluation parameters are added to Node class.

- Packet: Defines packet header and payload structure. It has source, destination, TTL, protocol identifier, sequence number, and payload fields as data members. Packet class has methods for integrity check, packing (serialization) and unpacking (deserialization) of generated packets.

- PhysicalEdgeOptions: Contains wavelengths and cost of each optical fiber as data members. PhysicalEdgeOptions has methods that determine whether there are available wavelengths on related fiber and reserve them if they are available.

- PhysicalEgde: Represents optical fiber in the optical layer of the simulation environment. The node pair which the fiber spans, a Boolean parameter for status of fiber and an instance of PhysicalEdgeOptions type for properties of fiber are the data members of PhysicalEgde class. It has methods for setting fiber options, getting source and destination node pairs and querying whether a specified fiber link is alive or not.
- PhysicalTopology: This is a singleton class which represents the physical topology of optical WDM network. It contains a list of PhysicalEgde instances as data member. There are methods for constructing a new physical edge, resource reservation for establishment of a new lightpath, resource deallocation of physical topology, shortest path lightpath establishment, and virtual topology design algorithm expressed in section 4.1.1.
- SimulationCommandsParser: This class is available in basic Fishnet and used as a command parser for simulator. A parser method for vt command, and a reconfiguration policy selector method are the most important contributions embedded to SimulationCommandsParser class. Also, simulation is terminated by a method implemented in this class. CommandsParser class is the base class of this class.
- Simulator: This class is already available in Fishnet. Main event handling mechanism of the simulation is performed by this class. Several modifications and additions are performed on the basic Simulator class. Generation of packet traffic for all nodes in the virtual topology, sending packets to a specified node, removal of control packets after a timeout period, reconfiguration transition routine for BE algorithm, and termination of simulation and calculation of performance parameters such as delay and packet loss are performed by the methods implemented in this class
- SpfLpf: Implements LPF and SPF algorithms expressed in sections 4.2.1 and 4.2.2 respectively. SpfLpf has methods for finding lightpaths which spans minimum and maximum number of physical hops, determination of

conflicting lightpaths, reconfiguration transition for LPF, and reconfiguration transition for SPF algorithms.

- StaticValues: Various different simulation parameters such as number of transceivers, wavelengths, lightpath capacity, mean packet size, MTU, control packet's timeout value, neighborhood discovery period, traffic generation parameters, and reconfiguration transition step interval are introduced in this class.
- TrafficGenerator: This class contains a Poisson arrival packet generator implementation and used to generate packet traffic during simulations in this study. Each packet is created one by one in a manner that current packet's information will be used in generation of the next packet.
- TrafficMatrix: Implements traffic matrix generation according to a traffic pattern given in section 5.2.1. TrafficMatrix class has methods for generation of random traffic matrices and rearrangement of traffic requests of the elements in generated traffic matrices.
- VirtualEdge: Represents the virtual edge (lightpath) of the virtual topology over the physical topology layer. It has nodes between which the lightpath is established, a Boolean value indicating whether it is alive or not, an instance of type VirtualEdgeOptions for properties of lightpath and a time value which stores info of when the next packet can be put onto the lightpath. VirtualEdge has methods such as querying whether a given node pair constitutes a ligthpath, a lightpath is alive or not, and scheduling packet transmission by considering delay, loss rate, and bandwidth of lightpath.
- VirtualEdgeOptions: Contains loss rate, delay, and bandwidth parameters of a lightpath of type VirtualEdge as data members and their getter/setter methods. An instance of type VirtualEdgeOptions is available in class VirtualEdge.
- VirtualTopology: This is a singleton class which represents the virtual topology established over the physical topology. As data member, it contains a list of VirtualEdge instances representing the lightpaths constituting the

virtual topology. There are various methods available for establishment/destruction of a new lightpath, getting a live lightpath between a given node pair, querying whether a specified lighpath is alive or not.

4 PROPOSED RECONFIGURATION ALGORITHMS

In this chapter, implemented virtual topology reconfiguration algorithms are described in detail. First, the virtual topology design algorithm used in the simulations is explained. Then, various reconfiguration techniques applied in this study are detailed.

4.1 Virtual Topology Design Algorithm

4.1.1 Greedy Logical Topology Design Algorithm (GLTDA)

This algorithm attempts to establish multiple parallel lightpaths between node pairs that exchange large amounts of traffic. Pseudocode of GLTDA is given in Figure 4.1. The following notation is used in GLTDA algorithm.

s	source node
d	destination node
t^{ij}	average traffic from source i to destination j in traffic matrix T
t_{max}^{sd}	maximum amount of traffic in traffic matrix T
δ^{s}_{O}	number of transmitters at source node s
δ^{d}_{I}	number of receivers at destination node d

Where update of t^{sd} in Step S3 of Figure 4.1 is replaced with $t^{sd} = t^{sd} - C$. C is capacity of a lightpath which is used to decrement the offered traffic t^{sd} after a lightpath has been established in the virtual topology.

This heuristic approach allows us to solve large problem instances of the virtual topology design problem since solution of the exact problem formulation is NP-Hard.

```
S1. Find  t^{sd}_{max} = max_{ij}(t^{ij})  and  t^{s'd'}_{max} = max_{i≠s∨j≠d}(t^{ij})
S2. If  t^{sd}_{max} = 0 then
        Go to S4
    Endif
S3. If  δ^s_O ≠ 0  and  δ^d_I ≠ 0  then
        Create a lightpath between  s  and  d
        Decrement  δ^s_O  and  δ^d_I
        Update  t^{sd} = t^{sd} − t^{s'd'}_{max}
        Go to S1
    Else
        Let  t^{sd} = 0
        Go to S1
    Endif
S4. Place required number of lightpaths at random, without
    violating the degree and wavelength constraints
```

Figure 4.1: Pseudocode of GLTDA

4.2 Virtual Topology Reconfiguration Algorithms

Virtual topology reconfiguration algorithms implemented in this study are given in detail in this section. There are two important issues involved in the reconfiguration of a network logical topology. One issue how to determine the target logical topology corresponding to the current logical topology and traffic matrix while the second one is how to determine a reconfiguration transition sequence shifting the current logical topology to the new one. In this study, the focus is on the latter problem and several reconfiguration algorithms that perform reconfiguration transition were implemented and their performance comparisons were evaluated.

4.2.1 Longest Lightpath First (LPF)

The LPF algorithm in **Takagi et al. (2006)** constructs the new lightpaths starting with the longest one and continues with shorter one according to the number of hops of the lightpaths in the physical topology. The reconfiguration sequence can be easily determined by sorting the lightpaths of the new logical topology, since the reconfiguration procedure depends only on the path hops in the physical topology. The longer a new lightpath is, the more it has the possibility of conflict with old lightpaths.

At each stage of reconfiguration transition, only a new lightpath is established and conflicting old lightpaths are removed from logical topology. The procedure continues until new logical topology is reached.

The conflicts among the old and new lightpaths may arise from using same transmitters at source node, receivers at destination and wavelengths through the path from source to destination nodes.

4.2.2 Shortest Lightpath First (SPF)

SPF algorithm in **Takagi et al. (2006)** works oppositely to LPF in the sense that SPF first constructs the shortest lightpath in the new logical topology according to the number of hops in the physical topology. This algorithm seems more efficient than LPF, since a lightpath with fewer hops in the physical topology may result in the less probability of conflict with the lightpaths of the old logical topology.

4.2.3 Minimal Disrupted Lightpath First (MDPF)

In contrast to LPF and SPF, MDPF in **Takagi et al. (2006)** algorithm calculates the effect of establishing each new lightpath and attemps to find out the optimal establishment sequence for the new lightpaths in order to minimize network disruption. An auxiliary graph, which represents the conflict relations between the new and old logical topologies, is introduced in implementation of MDPF. At each stage of the algorithm, a new lightpath which has minimum number of conflict relations with the old lightpaths is established.

The following notation is used in the MDPF algortihm.

l_i *i*th new lightpath

S set of the new lightpaths in conflict relation with the old ones

l'_i *i*th old lightpath

S' set of the old lightpaths in conflict relation with the new ones

$C(l_i)$ cost for setting up a new lightpath

$d(v)$ degree of vertex *v*

$N(v)$ neighborhood of vertex *v*

4.2.3.1 Creation of Auxiliary Graph

For the representation of conflicting new and old lightpaths, an undirected bipartite graph $G_a(V_a , E_a)$ where V_a and E_a denote the sets of vertices and edges, respectively, is introduced. The vertices denote the new and old lightpaths that have conflict relations and the edges denote the specific conflict relations between the conflicting new and old lightpaths. Conflicts of wavelength, transmitter, and receiver may be considered as conflict relationship.

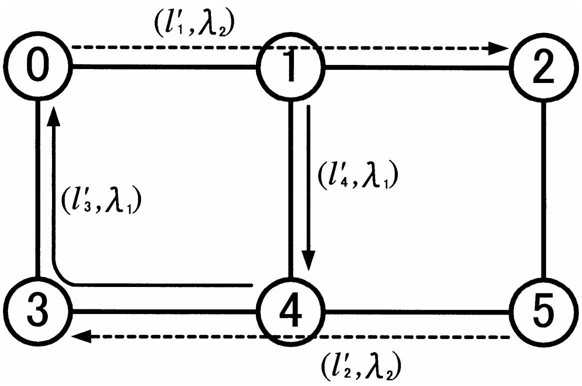

Figure 4.2: Old Lightpaths on the Physical Network

Figure 4.2 and Figure 4.3 show an example of conflicting new and old lightpaths on a physical topology. The conflict relations between the new and old lightpaths due to wavelength, transmitter and receiver are indicate by W, T, and R on edges, respectively on the auxiliary graph illustrated in Figure 4.4.

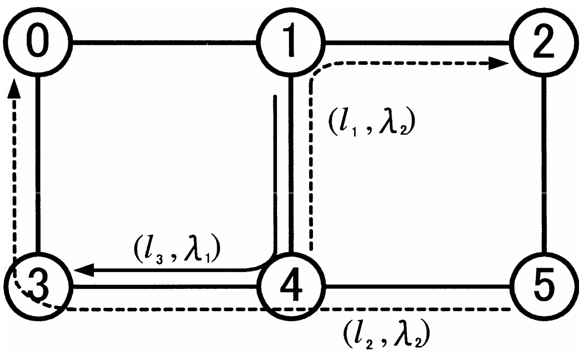

Figure 4.3: New Lightpaths on the Physical Network

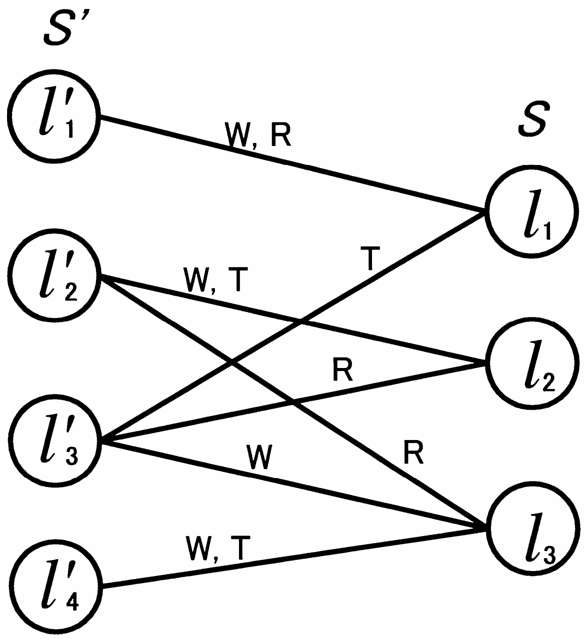

Figure 4.4: Auxiliary Graph for Figure 4.2 and Figure 4.3

4.2.3.2 Reconfiguration Procedure

In order to realize MDPF, the auxiliary graph introduced in the previous subsection is employed. At each stage of the algorithm, a set up cost is calculated for each new lightpath according to its degree in the auxiliary graph. Then, the lightpath with the least setup cost is selected and established. After that the auxiliary graph is updated. This procedure continues until the set of conflicting lightpaths is empty. Pseudocode of MDPF is represented in Figure 4.5.

4.2.4 Branch Exchange Sequences

Brach Exchange method proposed in **Labourdette et al. (1994)** shifts the old logical topology to the new one. Authors consider an approach where the network reaches some target connectivity graph through a sequence of intermediate graphs such that two successive graphs differ by a single branch exchange operation.

An auxiliary graph model is proposed to determine the minimum optimal number of branch exchange sequences for migration from old to new logical topologies. Authors stated that the size of decomposition of the auxiliary graph into vertex disjoint cycles equal the size of a sequence of BE operations that reconfigure network from an initial virtual topology to a target one.

Step 1. Create the auxiliary graph $G_a(V_a, E_a)$ based on the conflict relationship between the new and the old logical topologies.

Step 2. Calculate the establishment cost $C(l_i)$ for each new lightpath $l_i \in S$. The cost for establishing l_i is defined by the number of the old lightpaths in conflict relations with l_i, i.e., the number of the old lightpaths that should be disrupted in order to establish l_i, as follows.

$$C(l_i) = d(l_i), l_i \in S.$$

Step 3. Determine new lightpath ℓ with the least establishment cost:

$$\ell = \arg\min_{l_i \in S} C(l_i).$$

If there is more than one lightpath with the same least establishment cost, then choose the lightpath to establish that uses a transmitter or a receiver with the longest disruption time.

Step 4. Set up lightpath ℓ and update S and S' as follows:

$$S = S \setminus \{\ell\},$$
$$S' = S' \setminus N(\ell).$$

Update the auxiliary graph $G_a(V_a, E_a)$.

Step 5. Stop if $S = \emptyset$. Otherwise, go to Step 2.

Figure 4.5: Pseudocode of MDPF

Algorithm 0, which is a greedy algorithm and removes a cycle at each iteration, is implemented in this study. This is done by picking any vertex in the first stage of the auxiliary graph, and searching for a vertex disjoint shortest cycle uniquely from that vertex. The length of a cycle is assumed as the number of arcs it has.

4.2.4.1 Matrix Formulation and Construction of Auxiliary Graph

The topology of an N-node network can be represented as NxN matrix, M, where M_{ij} is the number of directed arcs from node i to node j, a non-negative integer.

Let M_1 be the matrix representing the network before reconfiguration, and let M_2 represent the target network. Example initial and target virtual topologies and related matrices are given in Figure 4.6 and Figure 4.7 respectively.

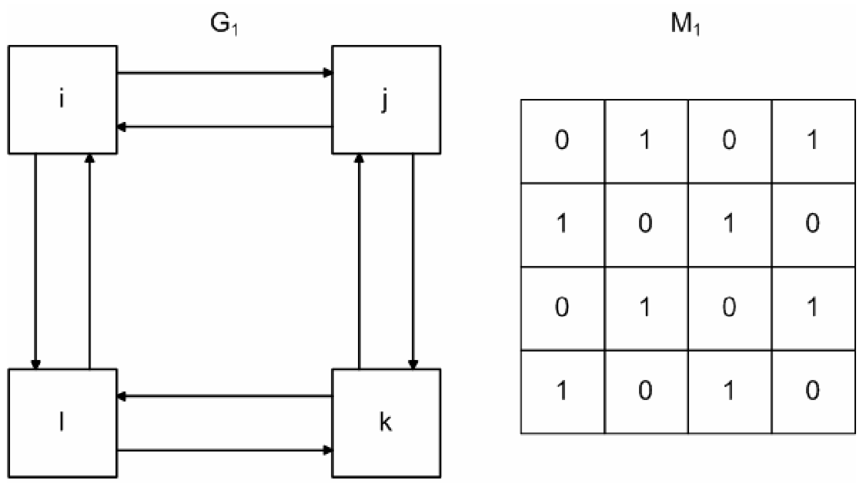

Figure 4.6: Initial Virtual Topology and Related Matrix

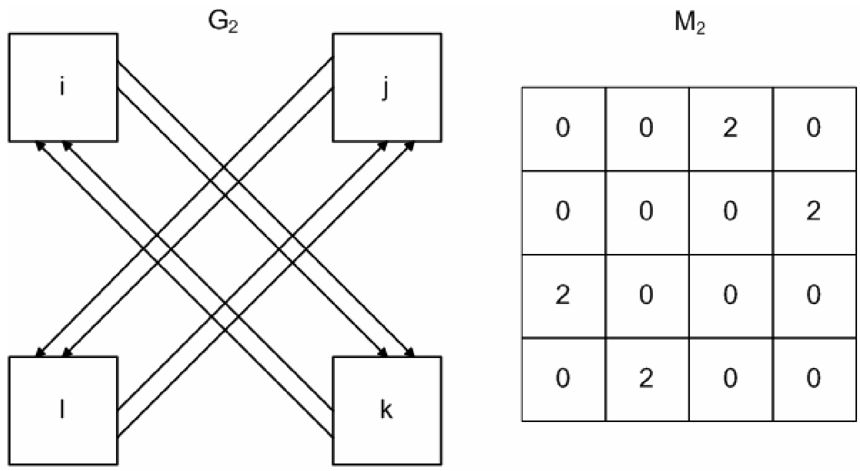

Figure 4.7: Target Virtual Topology and Related Matrix

A difference matrix $D = M_2 - M_{1,}$ is defined such that emphasizing the links which must be inserted or removed to effect the reconfiguration. Links to be inserted and deleted are represented as positive and negative entries in D respectively. An example of difference matrix calculated from the connectivity matrices in Figure 4.6 and Figure 4.7 is given in Figure 4.8.

Given D, create node labeled +1 or -1 for each entry of value +1 or -1. For entries in D of value +k create k nodes each labeled with +1, and for entries –k, create k nodes each labeled with -1. Position all such nodes in the plane as the entries are positioned in D, and associate with each node the corresponding ij indices of D. Connect -1 nodes to +1 in the same row, and connect +1 nodes to -1 nodes in the same column.

In Figure 4.9, an auxiliary graph derived from difference matrix in Figure 4.8 is given.

D

0	-1	+2	-1
-1	0	-1	+2
+2	-1	0	-1
-1	+2	-1	0

Figure 4.8: Difference Matrix Derived from Figure 4.6 and Figure 4.7

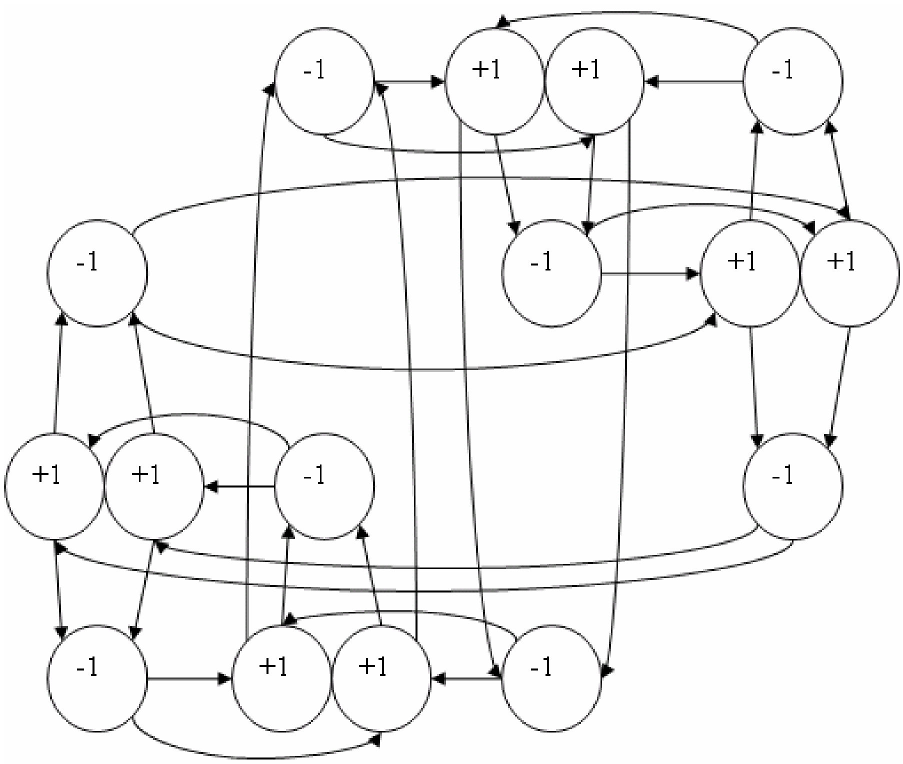

Figure 4.9: Auxiliary Graph Derived from Difference Matrix in Figure 4.8

5 SIMULATION EXPERIMENTS

In this chapter, simulation results for various metrics from implemented reconfiguration algorithms given in previous section are presented. First, physical topology and its constraints used in the simulations are detailed. Then, traffic generation pattern and IP packet structure described. After that, simulation metrics used in simulation experiments are explained. Then, performed simulation experiments are given and finally chapter concludes with the results obtained from these simulation experiments.

5.1 Physical Topologies Used in Simulations

Physical topology with 10 nodes and 21 edges presented in Figure 5.1 and NSFNET-like network with 16 nodes and 25 edges shown in Figure 5.2 are used during simulation experiments.

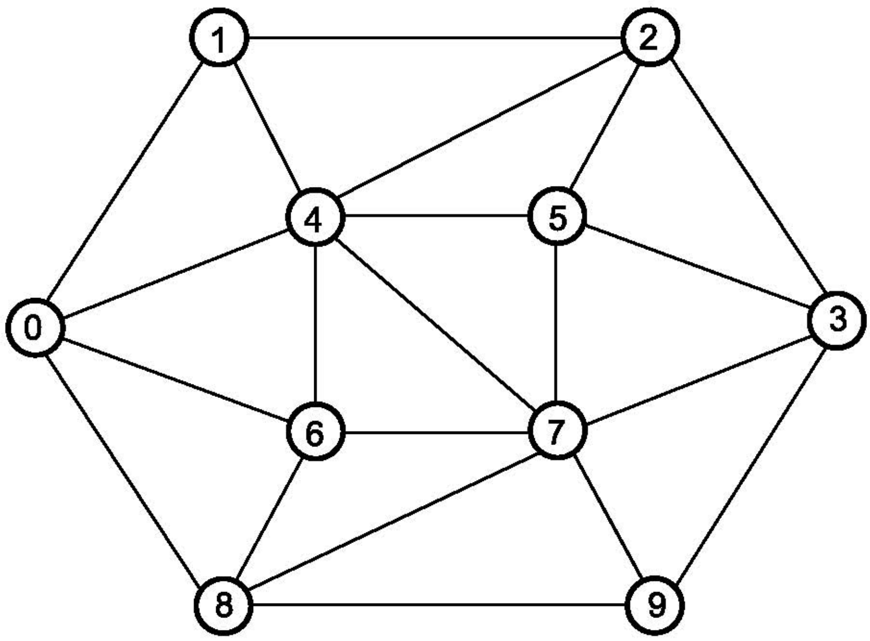

Figure 5.1: Physical Topology Used in Simulations

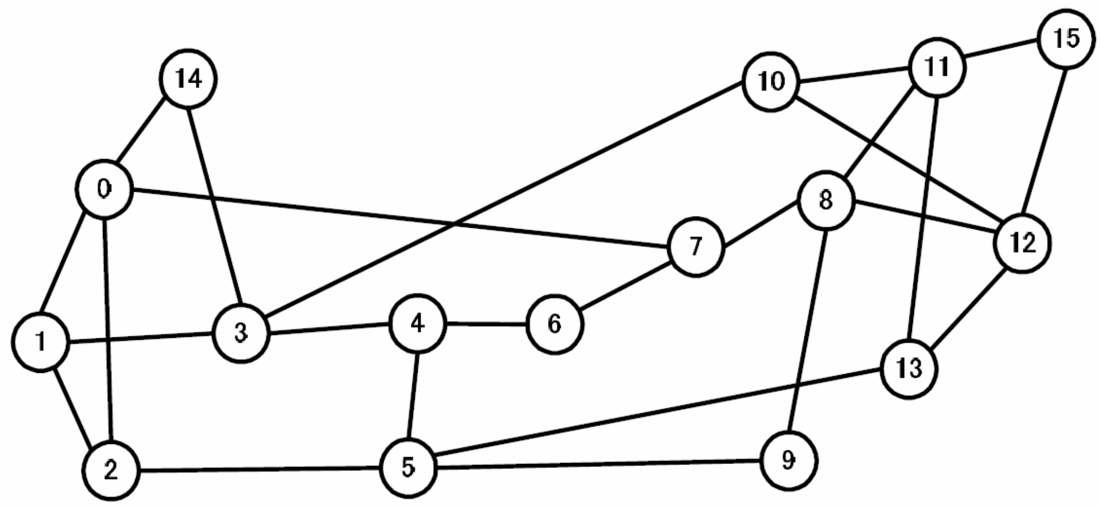

Figure 5.2: NSFNET Topology Used in Simulations

Each node is equipped with optical switches and each edge supports multiple wavelengths to enable optical communication. Furthermore, each node also assumed to have packet routers to support network layer communication, i.e. IP packet communication. The nodes of the network are assumed to be incapable of wavelength conversion. It is also assumed that each node in the network has same number of transceivers varying between 2 and 8. Each optical fiber is divided up to 8 wavelengths channel.

Virtual topology generated from Figure 5.1 and Figure 5.2 also has some restrictions that need to be clarified. At the time when the virtual topology is constructed, nodes of the virtual topology have no information about each others. Each node is capable of sending discovery packets to its neighbors to learn about them. Each discovery packet received by the neighbor node is sent back to the sender node. Sender node calculates the RTT time and accepts the half of this duration as the mean delay to its neighbor. This procedure is called as Neighborhood Discovery. After completion of Neighborhood Discovery, each node creates link state packets which contains information (neighbor identifier and delay) about its neighbors and broadcasts them to network. Each node receiving a link state packet broadcasts it also, therefore all nodes in the network learns every others' neighborhood information. After that, by each node a shortest path algorithm is employed to calculate the shortest path to every other node in the network and results are stored in routing tables. The whole procedure repeated for certain periods to inform nodes about dynamically changing network connectivity.

5.2 Traffic Generation Pattern and IP Packet Structure

This section explains generation of IP packet traffic with a given data rate and gives information about the structure of the generated IP packets used in the simulations.

5.2.1 Traffic Generation Pattern

Traffic matrices are randomly generated according to the method presented in **Banerjee & Mukherjee (2000)**. In this model, a certain fraction F of the traffic is uniformly distributed over [0, C/a] while the remaining traffic is uniformly distributed over [0, CY/a]. C, a and Y denote lightpath channel capacity, an arbitrary integer greater or equal to 1, and the average ration of traffic intensities between node pairs with high traffic values and node pairs with low traffic values respectively.

5.2.2 Generated IP Packets

Packet arrivals are modeled by using Poisson process. Mean packet size for Poisson process is selected as 1000 bytes. Maximum packet size is selected as 1500 bytes while 14 bytes of it constitute header information. Packet header has various fields that contain important information about the security and integrity of whole packet. Destination, source addresses, TTL (Time To Live), Protocol Identifier, Packet length, Sequence Number are the subfields of the packet header. Packet header fields and their size in packet header are shown in Figure 5.3.

Destination (1 byte)	Source (1 byte)	TTL (1 byte)	Protocol (1 byte)	Packet Length (2 byte)	Sequence Number (8 byte)

Figure 5.3: Packet Header

Brief description of the packet header fields are presented in the following

Destination: Destination node address to which this packet will be sent

Source: Source packet from which this packet originated

TTL: This field is set by the sender of the packet, and reduced by every host on the route to its destination to avoid a situation in which an undeliverable packet keeps circulating on network

Protocol: Identifies the type of this packet. A packet may be Discovery, Link State or Transport Packet

Packet Length: The total length of this packet.

Sequence Number: This field is set by source router and incremented for each packet produced. Sequence number enables other routers keep track of all the (source router, sequence) pairs they received to avoid duplicate transmission of packets.

Also, each packet has a payload subfield which contains actual data to be transmitted through the network

There are three important packet types used in the simulations.

Discovery packet: This type of packet is used by a node in order to learn about its neighbors. In addition to its header, it contains "Discovery" string as payload to point out that it is a discovery packet. When discovery packet is received by a neighbor node, it is immediately sent back to the source node from which that packet is originated. Discovery packets are generated periodically for acquisition of neighborhood information.

Link State Packet: This packet contains all neighborhood information of a node. Each node in network generates these types of packets and broadcast them. Like Discovery packets this type of packets are also created periodically in this simulation study.

Transport Packet: Discovery and Link State packets are control packets that provide stable operation of the network. Transport packets contain actual data that need to be transmitted in their payload field. In this study, payload field of a Transport packet can carry between 64 and 1486 bytes of data.

5.3 Numerical Results

Packet loss and delay are used as the main simulation metrics in simulations. Packet loss is calculated as the ratio of dropped total packets and generated total packets. Discovery and Link State packets are not considered in calculation of packet loss parameter.

Packet delay is calculated as the average duration of transmission of a single bit in seconds/Gbit. A packet has to reach its destination node successfully in order to be included in evaluation of packet delay parameter. Each packet's transmission time is divided by packet's size and summed up; obtained total sum is divided to total number of the successfully transmitted packets. Resulting value is denominated as packet delay.

First, the situation in which the traffic changes but the initial virtual topology remains the same was observed. This situation was called as "no reconfiguration" scenario and packet delay was used as the main performance comparison criteria in this scenario. Second scenario was named as "reconfiguration" that packet losses were inspected during reconfiguration time before the neighborhood discovery and routing table stabilization occurs. These experiments described above were applied to both of physical topologies described in section 5.1 under various different traffic conditions. Different traffic matrices with the same amount of total traffic were derived by interchanging the whole matrix elements randomly. The results presented in this chapter are the average values obtained from 10 simulation runs.

An initial traffic matrix with 0.37 Gbps total traffic was applied to 10 node topology given in Figure 5.1 for examination of no reconfiguration scenario. Traffic matrix which is called "initial traffic matrix" was generated according to the method given in section 5.2.1 with parameters selected as C = 10 Gbps, Y = 5, F = 0.8 and a = 1920. Traffic matrix derived by interchanging elements of initial traffic matrix was named as "second traffic matrix". According to the scenario, a new virtual topology is established according to the initial traffic matrix. After 5 seconds, packet traffic was produced for 100 milliseconds with respect to the first/second traffic matrix.

Then, simulation was terminated at time 6 seconds. Table 5.1 shows packet delays in seconds/Gbit versus number of transceivers in the case of no reconfiguration.

Table 5.1: Packet Delays for 0.37 Gbps Total Traffic (No Reconfiguration)

seconds/Gbit x 10^{-3}	Number of Transceivers			
	2	4	6	8
Initial Traffic Matrix	145	96	71	57
Second Traffic Matrix	168	118	83	64

Each optical fiber is assumed to have 8 wavelength channels. The row tagged with "Second Traffic Matrix" shows increased packet delays due to avoidance of reconfiguration. There is an increase in packet delay for all number of transceivers which leads to degradation in performance and makes reconfiguration inevitable. One additional note on Table 5.1 is that with increase of transceivers the amounts of delays reduce since more lightpaths can be established with larger number of transceivers. An increase in the number of lightpaths leads to a decrease in delay values since the total bandwidth of network increases.

To observe what happens during reconfiguration and compare performance of various reconfiguration algorithms following scenario was simulated. A new virtual topology is established according to the initial traffic matrix in Table 5.1. After 5 seconds, packet traffic was produced for 100 milliseconds with respect to the second traffic matrix in Table 5.1 and virtual topology reconfiguration according to second traffic matrix is launched at the same time. After 1 second, simulation was terminated at time 6 seconds. In this simulation it is assumed that 8 wavelengths are available and neighborhood discovery and reconfiguration transition periods are selected as 1 second and 1 millisecond respectively. Packet loss during reconfiguration transition was calculated for various reconfiguration algorithms and results were shown in Table 5.2. Instant reconfiguration means all reconfiguration transition takes place instantly in a single step. The packet loss in Table 5.2 occurs due to inconsistency between the new virtual topology and routing tables at the nodes, since routing tables are still not updated when reconfiguration occurs.

Table 5.2: Packet Loss During Reconfiguration for 0.37 Gbps Total Traffic

Packet Loss (%)	Number of Transceivers		
	2	4	6
Instant Reconfiguration	62,98	31,28	6,55
LPF	61,98	36,04	15,30
SPF	60,31	30,59	14,46
MDPF	58,34	26,62	11,85
Branch Exchange	61,58	30,43	6,03

Reconfiguration algorithms are especially successful at lower number of system resources due to limited number of established lightpaths. MDPF has the lowest packet loss with 2 and 4 transceivers. Simple heuristics of SPF and LPF has close packet loss values and their performance is lower than MDPF. LPF and SPF have shown an unstable performance during simulations. In this case, SPF is inconsiderably better than LPF in all cases since it selects shorter new lightpaths that have lower probability to have conflict relation with old lightpaths and LPF has the worst performance for all number of transceivers. But, in some simulations which will be given further in this study, performance of SPF and LPF varies. Branch Exchange algorithm has similar results with SPF and LPF at lower resource utilizations. Its performance increases with the increase of transceivers in the system and becomes closer to instant reconfiguration at higher number of transceivers. For all algorithms, packet loss tends to decrease with an increase in the number of transceivers since more lightpaths can be established with increasing number of transceivers.

Another initial traffic matrix with denser total traffic of 1,39Gbps was applied to 10 node physical topology given in Figure 5.1. The traffic generation parameters selected as C = 10 Gbps, Y = 5, F = 0.8 and a = 480 which leads to four times denser traffic than the previous simulation experiment. Packet delays for various numbers of transceivers are shown in Table 5.3. Each fiber is assumed to have 8 wavelength channels.

Table 5.3: Packet Delays for 1.39 Gbps Total Traffic (No Reconfiguration)

seconds/Gbit x 10^{-3}	Number of Transceivers			
	2	4	6	8
Initial Traffic Matrix	169	102	77	58
Second Traffic Matrix	220	136	87	69

Table 5.3 has higher delay values compared with Table 5.1, since the total amount of traffic applied to physical topology increased. Packet losses of reconfiguration scenario for the same traffic matrices used in Table 5.3 is presented in Table 5.4. In Table 5.4, it is assumed that 8 wavelengths are available, neighborhood discovery and reconfiguration transition periods are selected as 1 second and 1 millisecond respectively.

Table 5.4: Packet Loss During Reconfiguration for 1.39 Gbps Total Traffic

Packet Loss (%)	Number of Transceivers		
	2	4	6
Instant Reconfiguration	79,88	31,58	5,28
LPF	79,04	38,82	16,77
SPF	77,56	35,28	14,64
MDPF	74,06	24,45	10,05
Branch Exchange	77,69	30,18	5,39

NSFNET topology represented in Figure 5.2 was also used in delay and packet loss simulations. Results for two different pairs of traffic matrices for NSFNET topology will be given in this chapter. Number of wavelengths was selected as 8, reconfiguration transition period as 1 millisecond, and neighborhood discovery as 1 second. Table 5.5 and Table 5.6 represents packet delay and packet loss measurements respectively with traffic generation parameters selected as C = 10 Gbps, Y = 5, F = 0.8 and a = 1920.

Table 5.5: Packet Delays in NSFNET for 0.997 Gbps Total Traffic (No Reconfiguration)

seconds/Gbit x 10^{-3}	Number of Transceivers			
	2	4	6	8
Initial Traffic Matrix	175	122	108	100
Second Traffic Matrix	212	156	138	133

As it can be seen in Table 5.6, Branch Exchange algorithm has no results for 4 and 6 transceivers. BE algorithm assumes that the transceivers of nodes must be fully utilized. Thus, BE can not be operable in situations that violate this condition. But virtual topology design algorithm used in this study does not guarantee full utilization of network resources for all number of resources. In Table 5.6, full utilization of transceivers was achieved for 2 transceivers. On the other hand, utilization of all transceivers was not achieved for larger number of transceivers such as 4 and 6. Therefore, no results are obtained for 4 and 6 transceivers.

Table 5.6: Packet Loss in NSFNET During Reconfiguration for 0.997 Gbps Total Traffic

Packet Loss (%)	Number of Transceivers		
	2	4	6
Instant Reconfiguration	88,18	62,44	40,83
LPF	84,40	65,43	52,08
SPF	85,21	58,48	49,97
MDPF	80,58	54,58	37,45
Branch Exchange	84,71	-	-

A more intensive traffic with parameters of C = 10 Gbps, Y = 5, F = 0.8 and a = 960 was also applied to NSFNET topology. Table 5.7 and Table 5.8 show the results of packet delays and packet losses in "no reconfiguration" and "reconfiguration" scenarios respectively. Table 5.7 has higher packet delays for same number of transceivers compared to delays in Table 5.5, since it was exposed to a nearly two times larger amount of traffic than the traffic in Table 5.5.

Table 5.7: Packet Delays in NSFNET for 2.16 Gbps Total Traffic (No Reconfiguration)

seconds/Gbit x 10^{-3}	Number of Transceivers			
	2	4	6	8
Initial Traffic Matrix	204	125	111	103
Second Traffic Matrix	240	158	133	131

Observations derived from Table 5.1 and Table 5.2 are also valid for Table 5.7 and Table 5.8. Additionally, BE algorithm has lower practicability according to the other algorithms implemented in this study since it needs full utilization of transceivers for its applicability.

Table 5.8: Packet Loss in NSFNET During Reconfiguration for 2.16 Gbps Total Traffic

Packet Loss (%)	Number of Transceivers		
	2	4	6
Instant Reconfiguration	84,39	61,08	34,66
LPF	80,76	62,73	46,81
SPF	79,85	58,08	41,85
MDPF	78,03	52,82	32,40
Branch Exchange	81,01	-	-

Reconfiguration techniques investigated in this study can be analyzed according to the number of reconfiguration steps that they require. Instant reconfiguration performs whole reconfiguration transition in one single step. Each of LPF, SPF and MDPF algorithms establishes a new lightpath at each reconfiguration stage while BE algorithm can establish multiple lighpaths in a single reconfiguration transition period. Thus, BE algorithm can terminate quickly than LPF, SPF and MDPF algorithms.

6 CONCLUSION

Reconfigurability of optical WDM networks provides them an adaptable infrastructure for dynamically varying traffic characteristics of today's bandwidth hungry communications applications. Although optical networks seem to be the most powerful candidates to meet today's bandwidth requirements, there still exists absence of intelligent and efficient mechanisms for integration of optical WDM networks with upper layers. IP-WDM integration and management of IP traffic over optical networks appears to be an important problem that needs to be solved.

The effects of virtual topology reconfiguration on Internet Protocol (IP) packet traffic in IP over WDM networks were studied in this thesis in order to understand the relations and problems between IP and WDM layers. For this purpose, an IP simulator which is unaware of lower level communication infrastructure was implemented based on Fishnet project. Fishnet project was customized to simulate the functionalities of a network layer protocol that supports creation and transmission of communication packets with respect to a given traffic pattern over an underlying optical WDM network. It is possible to have packet delay/loss during reconfiguration process in an optical network, since old lightpaths are destroyed and new lightpath are established in virtual topology reconfiguration. There are lots of algorithms proposed for reconfiguration of optical network in the literature that each of them considers different performance metrics. An extensive literature survey was performed and various reconfiguration algorithms such as SPF, LPF, MDPF, and BE were implemented and their performance comparisons were evaluated by means of packet delays/losses on developed framework. Among the studied algorithms, MDPF seems to have the best packet loss performance. On the other hand BE algorithm needs least number of reconfiguration transition steps, but is not always applicable due to its dependency on fully utilization of transceivers. LPF and SPF are simple heuristics an included in this study just for comparison of performance with other algorithms.

Various reconfiguration algorithms implemented in this thesis will inform us about the effect of reconfiguration at user viewpoint such as packet delays/losses. One additional aim of this thesis is to be able to compare and discuss the performance of various virtual topology reconfiguration algorithms on the implemented IP framework. This thesis can be extended to derive more performance metrics for observation of network performance and development of automated mechanisms for intelligent management of optical WDM networks by using implemented two layered simulation framework.

REFERENCES

Agrawal, G. P., 1997. Fiber-Optic Communication Systems, John Wiley & Sons

Alfouzan, I. and Jayasumana, A., 2001. Dynamic reconfiguration of wavelength-routed WDM networks, *26th Annual IEEE Conference on Local Computer Networks, 2001. Proceedings. LCN 2001*, 14-16 Nov. 2001, p.477-485

Bala, K., Ellinas, G., Post, M., Shen C.C., Wei, J. and Antoniades, N., 1996. Towards hitless reconfiguration in WDM optical networks for ATM transport, *Global Telecommunications Conference, 1996. GLOBECOM '96*, 18-22 Nov. 1996, Vol.1, p.316-320

Baldine, I. and Rouskas, G.N., 2001. Traffic adaptive WDM networks: a study of reconfiguration issues, *Journal of Lightwave Technology*, Vol.19, No.4, p.433-455

Banerjee, D. and Mukherjee, B., 2000. Wavelength-routed optical networks: Linear formulation, resource budgeting tradeoffs, and a reconfiguration study, *IEEE/ACM Transactions on Networking*, Vol.8, Iss.5; p.598-607

Bhandari, S. and Park, E.K., 2005. Dynamic reconfiguration for optical network, *14th International Conference on Computer Communications and Networks, 2005. ICCCN 2005*, 17-19 Oct. 2005, p.243-248

Din, D., A genetic algorithm for solving virtual topology configuration transition problem in WDM network, *Computer communications*, 26/02/2007. Vol.30, Iss.4; p.767

Gillani, B., Kent, R.D. and Aggarwal, A.K., 2005. Topology reconfiguration mechanism for traffic engineering in WDM optical network, *19th International Symposium on High Performance Computing Systems and Applications, 2005. HPCS 2005*, 15-18 May 2005 p.161-167

Gencata, A. and Mukherjee, B., 2003. Virtual-topology adaptation for WDM mesh networks under dynamic traffic, *IEEE/ACM Transactions on Networking*, April 2003. Vol.11, No.2, p.236-247

Golab, W. and Boutaba, R., 2004, Policy-driven automated reconfiguration for performance management in WDM optical networks, *IEEE Communications Magazine*, Vol. 42, Iss.1, p. 44-51.

Green, P. E., 1992. Fiber Optic Networks, Prentice Hall

Gribble, S., 2005. Introduction to Fishnet, http://www.cs.washington.edu/education/courses/cse461/05au/projects/fishnet-intro.pdf

Hinton, H. S., 1993 An Introduction to Photonic Switching Fabrics, Plenum Press.

Ilyas, M. and Mouftah, H.T., 2003. The Handbook of Optical Communication Networks, CRC Press.

Kim, B., Eom, J.H., Park, J. and Chae, C.J., 1999. A Lightpath Routing Reconfiguration Algorithm for WDM Optical Networks, *Fifth Asia-Pacific Conference on Communications and Fourth Optoelectronics and Communications Conference. APCC/OECC'99*, 18-22 Oct. 1999, Vol.1, p.11-14

Kocak, O., Cavdar, C., Gençata, A. and Buzluca, F., 2004. An efficient heuristic for virtual topology reconfiguration in optical WDM networks, *The 6th International Conference on Advanced Communication Technology, 2004*. Vol.2, p.611-614

Labourdette, J.F.P., Hart, G.W. and Acampora, A.S., 1994. Branch-exchange sequences for reconfiguration of lightwave networks, IEEE Transactions on Communications, Vol.42, No.10, p.2822-2832

Lee, K., Zhang, L. and Youn, C.H., 2003. An adaptive virtual topology reconfiguration policy in multi-wavelength optical Internet, *European Transactions on Telecommunications September/October, 2003*. Vol.14, Iss.5, p.417-422

Liu, K.H., Liu, C., Pastor, J.L., Roy, A. and Wei, J.Y., 2002. Performance and testbed study of topology reconfiguration in IP over optical networks, *IEEE Transactions on Communications*, October 2002, Vol.50, No.10, p.1662-1679

Mohan, G., Ernest, P.H.H. and Bharadwaj V., 2003. Virtual topology reconfiguration in IP/WDM optical ring networks, *Computer Communications*, Vol.26, Iss.2; p.91

Mouftah, H. T. and Elmirghani, J. M. H., 1998. Photonic Switching Technology: Systems and Networks, IEEE Press

Narula-Tam, A., Lin, P.J. and Modiano, E., 2000. Wavelength requirements for virtual topology reconfiguration in WDM ring networks, *IEEE International Conference on Communications, 2000. ICC 2000*, Vol.3, p.1650-1654

Narula-Tam, A. and Modiano, E., 2000. Dynamic load balancing in WDM packet networks with and without wavelength constraints, *IEEE Journal on Selected Areas in Communications*, Vol.18, No.10, p.1972-1979

Prathombutr, P., Stach, J., Park, E.K. and Tak, S.W., 2004. Model for series of reconfigurations in wavelength-routed optical networks, *Proceedings - International Conference on Computer Communications and Networks, ICCCN*, 01/01/2004, p.437-443

Qin, T., Zhang, H. and Guo, Y., 2002. A Modified Simulated Annealing Algorithm for Joint Configuration of the Optical and Electrical Layer in Intelligent Optical Networks, *IEEE Global Telecommunications Conference*, Vol.3; p.2847-2850

Ramamurthy, B. and Ramakrishnan, A., 2000. Virtual Topology Reconfiguration of Wavelength-routed Optical WDM Networks, *Global Telecommunications Conference, 2000*, Vol.2, p.1269-1275

Ramaswamy, R. and Sivarajan, K., 2001. Optical Networks: A Practical Perspective, Morgan Kaufmann

Rouskas, G.N. and Ammar, M.H., 1995. Dynamic reconfiguration in multihop WDM networks, *Journal of High Speed Networks*, Vol.4, Iss.3, p.221-238

Saad, M., 2005, Reconfiguration with no service disruption in multifiber WDM networks, *Journal of Lightwave Technology*, October 2005. Vol.23, No.10, p.3092–3104

Sinha, S. and Murthy, C.S.R., 2005. Information Theoretic Approach to Traffic Adaptive WDM Networks, August 2005. *IEEE/ACM Transactions on Networking*, Vol.13, No.4, p.881-894

Sivalingam, K.M. and Subramaniam, S., 2002. OPTICAL WDM NETWORKS Principles and Practice, Kluwer Academic Publishers

Sreenath, N. and Murthy, C.S.R., 2002. On-line reconfiguration of virtual topologies in wavelength-routed WDM networks, *Journal of High Speed Networks, 01/01/2003*. Vol.12, Iss.3-4, p.141-169

Stosic, J. and Spasenovski, B., 2003. Practical models for design and reconfiguration of virtual topology in optical transport networks, *6th International Conference on Telecommunications in Modern Satellite, Cable and Broadcasting Service, 2003. TELSIKS 2003*, 1-3 Oct. 2003, Vol.1, p.67-70

Sumathi, M. and Vanathi, P.T., 2005, Minimizing Congestion in Optical WDM Networks for Dynamic Traffic, *IEEE Indicon 2005 Conference, Chennai, India*, 11-13 Dec. 2005, p.101-104

Tak, S., Prathombutr, P. and Park, E.K., 2007. An efficient technique for a series of virtual topology reconfigurations in WDM optical networks, *Computer communications*, 26/03/2007. Vol.30, Iss.6, p.1301-1314

Takagi, H., Zhang, Y. and Takagi, H., 2006. Reconfiguration Heuristics for Logical Topologies inWide-Area WDM Networks, *IEICE Transactions on Communications*, Vol.E89-B, No.7, p.1994-2001

Tanenbaum, A.S., 2002. Computer Networks, Prentice Hall PTR

Xu S., Sezaki, K. and Tanaka, Y., 2004. A Two-Stage Simulated Annealing Logical Topology Reconfiguration in IP over WDM Networks, *11th International*

Telecommunications Network Strategy and Planning Symposium. NETWORKS 2004, 13-16 June 2004, p.327-332

Yang, X. and Ramamurthy, B., 2002. An Analytical Model for Virtual Topology Reconfiguration in Optical Networks and A Case Study, *Eleventh International Conference on Computer Communications and Networks, 2002. Proceedings*, 14-16 Oct. 2002, p.302-308

Yeh, H.Y., Chen, C. and Chen, Y.Y., 2005. Virtual topology reconfiguration in hierarchical cross-connect WDM networks, 12-14 May 2005, *High Performance Switching and Routing, 2005. HPSR. 2005 Workshop*, p.515-519

Zhang, Y., Murata, M., Takagi, H. and Ji, Y., 2005. Traffic-based reconfiguration for logical topologies in large-scale WDM optical networks, *Journal of Lightwave Technology*, Vol.23, Iss.10, p.2854-2867

Zheng J., Zhou, B. and Mouftah, H.T., 2004. Virtual topology design and reconfiguration of virtual private networks (VPNs) over all-optical WDM networks, *Photonic Network Communications*, Vol.7, Iss.3, p.255-266

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