2005

Heuristic for the design of fault tolerant logical topology.

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Heuristic for the Design of Fault Tolerant Logical Topology

By

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A Thesis
Submitted to the Faculty of Graduate Studies and Research
Through the School of Computer Science
In Partial Fulfillment of the Requirements for
The Degree of Master of Science at the
University of Windsor

Windsor, Ontario, Canada

September 2005

Your file Votre référence
ISBN: 0-494-09727-2
Our file Notre référence
ISBN: 0-494-09727-2

Abstract

Heuristic for fault tolerant logical topology design for WDM optical networks. (Under supervision of Dr. Arunita Jaekel).

Wavelength division multiplexing (WDM) in optical fiber networks is widely viewed as the savior for its potential to satisfy the huge bandwidth requirement of network users. Optical cross connect (OCX) in WDM network facilitates the switching of signal on any wavelength from any input port to any output port. As a result, it is possible to establish ligthpaths between any pair of nodes. The set of lightpaths established over fiber links defines logical topology. The high link capacity of fiber in WDM network has the drawback that a single link failure may result in huge amount of data loss (and revenue). Consequently, this gives rise to the problem of designing logical topologies to optimize network resources of interest for a set of traffic demands and a set of failure scenario.

In our thesis, we proposed a heuristic approach for the design of fault tolerant logical topology. Our design approach generalizes the "design protection" concept and enforces wavelength continuity constraint in a multi-hop optical network. In our work, we first designed logical topology for fault free state of the network. We, then, added additional lightpaths for each single link failure scenario. Numerical results clearly show that our approach outperforms Shared path protection and Dedicated path protection. Our simulation result shows that our approach is feasible for large networks.

Keywords: WDM, Wavelength Routed Networks, Physical Topology, Logical Topology, Single-Hop, Multi-Hop, Routing and Wavelength Assignment (RWA), Survivability, Protection, Restoration, MILP, Heuristic.

Dedication

TO MY MOTHER, WIFE, SISTER AND BROTHERS

Mina Saha,

Moni Saha,

Mridula Roy,

Tapas Saha,

And

Suman Saha

Acknowledgement

I am very pleased to take this opportunity to thank few very important people who helped me a lot during the whole process of my graduate study.

I would like to express my deep appreciation to my supervisor, Dr. Arunita Jaekel. The work could not be accomplished without her continuous invaluable comment, extensive guidance, encouragement and support.

I would like to thank my committee internal reader Dr. Subir Bandyopadhyay and external reader Dr. Narayan Kar, for their time committed and instructive suggestions and comments. Special thanks to Dr. Morrissey for chairing my theses defense.

I would like to thank my wife, mom, sister and brothers for their endless love, care and for always being there for me.

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1.0 Introduction

1.1 Introduction to the Thesis

Optical networks, with their low loss, high bandwidth and low error rates, are needed to satisfy the huge bandwidth requirements of the internet, to-day and in the foreseeable future. Such networks are being deployed as the backbone for nationwide or global wide area networks. Wavelength-division multiplexing (WDM) [Muk97], [Gre92] technology allows a single optical fiber to carry data on several independent communication channels simultaneously. WDM divides the huge bandwidth of a fiber into many non-overlapping channels, where each channel is assigned a specific carrier wavelength. This dramatically increases the amount of traffic that can be supported on a single fiber. A WDM network consists of a set of nodes (equipped with optical devices such as transmitters/receivers, optical routers and add/drop multiplexers) interconnected physically by optical fibers. This defines the *physical* topology [RD00], [RS96] of the network.

A *logical* topology [RD00], [RS96] is overlaid upon the physical topology by establishing *lightpaths* [RD00] between the nodes [NMB03]. A lightpath is an end-to-end, all optical communication channels from a source node s to a destination node d. In the absence of wavelength converters [Joe93], a lightpath is assigned the same channel on all links that it traverses. This is known as *wavelength continuity constraint* [Bra90]. Due to both technology and cost limitations, most networks enforce the wavelength continuity constraint and we also follow this restriction in this thesis. A *logical* topology consists of the set of end-nodes in the physical topology and a set of *logical* edges, where there is a logical edge from a node i to a node j, if a lightpath has been established from i to j. Once the lightpaths have been established, the physical topology is irrelevant for determining a routing strategy to handle the traffic demand between end-nodes.

The design of a suitable logical topology and an appropriate routing over the topology is an important problem in the area of WDM network design. The main objectives are to design a topology that

- Will allow optimal routing of the traffic demands between all node pairs
- Can be accommodated using the underlying physical topology
- Minimizes the cost of the network resources needed to implement logical topology

Mixed integer linear program (MILP) formulations have been proposed [MRBM94], [MRBM96], [KS98], [RS96] to solve the complete design problem, given above. Such formulations are very complex and become computationally intractable for even moderate sized networks [HABJ+02]. Therefore, most existing approaches separate the problem of logical topology design and optimal routing over the logical topology. Typically, heuristics are used to design the logical topology and either an LP formulation or heuristics are used to determine the routing.

1.2 Motivation

Since a single link can carry tens of terabits of data per second with extremely low loss, a huge amount of data is affected in the event of network failure. This can lead to significant data (and revenue) loss, even if a link is down for a short period of time [ZKSY+03]. Therefore, survivability of WDM networks is a very important issue and there has been intensive research interest, in recent years, in the area of survivable WDM network design [ACL97], [Fum99], [AMM00], [CPTD98], [ZS00], [GR00], [EN01], [GR00a], [RM99a], [Wu95], and [Wu92]. There are three types of network failure: link failure, node failure, and wavelength failure. Link failure means that the transport fibers in the physical layer are damaged; node failure occurs when the workstations or concentrators in the physical layer are damaged; wavelength failure implies that one or more channels in a fiber are damaged. The most common type of failure in WDM networks is link failure [ZS00]. A single physical link failure may correspond to multiple logical link failures in a WDM network. Consequently, two-connected logical topologies, such as rings or meshes routed on a WDM physical topology, may become disconnected after a single physical link failure. Two main techniques that have been proposed to handle such failures are:

i) Protection based techniques [CB98], [EHS00], [SG00] and

ii) Restoration based techniques [DDHH+98], [LDS98], [CGK92], [DG00], and [RM99b].

Protection techniques are based on pre-planned links or paths to recover from network failure. Spare capacity has to be reserved during the lightpath setup phase, so that data can be re-routed around the affected link/lightpath, when a failure occurs. In a traditional path protection scheme, if a logical edge is established from node *i* to node *j*, then two lightpaths are actually set up. The first lightpath, called the *primary* lightpath, carries the data under normal fault-free conditions. The second lightpath is the *backup* lightpath and is edge-disjoint with the corresponding primary lightpath. In the case of a network fault, which disables the primary lightpath, the corresponding backup lightpath will be used. Since the primary and backup paths are edge-disjoint, there will always be a valid path from node *i* to node *j*, for any single link failure. The drawback of this approach is that the resources allocated to the backup paths remain idle, and are wasted under normal conditions.

Restoration based techniques dynamically search the spare capacity in the network to restore the affected services, *after* a network failure is detected [RM99b]. There is no allocation of resources for backup paths at design time. Such techniques are more efficient in terms of resource utilization. But, it takes longer to restore services (since backup paths are not known in advance) and there is no guarantee that all affected lightpaths can be restored.

Both protection and restoration schemes require the creation of new lightpaths, when a fault is detected. For protection, the routes and channels for the new lightpaths are known, and the corresponding resources are allocated, in advance. For restoration, this must be done dynamically, after the fault is detected. In this thesis, we propose a new methodology for the design of fault tolerant logical topologies in WDM optical networks, based on the concept of survivable routing [SRM02]. In this approach, we route the logical lightpaths onto physical links in such a way that the logical-topology remains connected in the event of a link failure. We also guarantee that the surviving logical topology, after any single link failure, will have sufficient capacity to accommodate the entire traffic demand. Therefore, recovery from a failure can be achieved simply through traffic rerouting. The proposed scheme is much more efficient, in terms of resource utilization, compared to protection based schemes. This is because there is no need to allocate resources for backup paths, which remain idle most of the time.

1.3 Problem Statement

The logical topology design problem for WDM networks consists of two components:

i) determining a set of logical edges that can accommodate the given traffic demand and

ii) determining a physical route and channel for the lightpath(s) associated with each logical edge. This is also known as the *routing and wavelength assignment* (RWA) problem.

The above two components are inter-related and are not independent of each other. Both MILP formulations [KS98] and heuristics [RS96] have been proposed for solving the above two components together. In order to reduce the complexity of the problem, the two components are often treated separately. If the set of lightpaths is given, the topology design problem is reduced to the pure RWA problem, which in turn can be broken into the routing sub-problem and wavelength assignment sub-problem.

The logical topology design problem assumes that the network traffic demand and an underlying physical network are given, and an optimal logical topology and RWA need to be determined to accommodate the traffic demand. The information needed for the design includes the topology of the physical network, the characteristic of the fiber (i.e. number of channels that are available on each fiber) and the number of transmitters and receivers available in the network. We assume that the traffic demand is relatively stable and does not change quickly with time.

The fault tolerant logical topology design problem considered in this thesis can then be stated as follows:

Given

- An existing undirected physical topology in which i) each node is equipped with a limited number of tunable transmitters and receivers, and ii) nodes are connected by optical fibers that support a fixed number of wavelengths.
- A traffic demand $T = (t_{sd})$, where t_{sd} represents the amount of traffic flow from a source node s to a destination node d.

Determine a logical topology (i.e. set of lightpaths) such that:

- The cost of the topology is minimized
- The topology remains connected and is capable of handling the entire traffic demand, under all single link failure scenarios
- A feasible RWA can be determined for the set of lightpaths, over the underlying physical network

1.4 Solution approach

An exact MILP formulation of the above logical topology design problem grows very quickly as the network size increases. This problem and some of its sub-problems are known to be NP-hard [MRBM94], [BM96], [DR00], and [KS98] and the formulation becomes computationally intractable, even for moderate size networks. Therefore, it is not practical to attempt to solve this problem exactly. Heuristics which can generate correct, feasible solutions are required.

In this thesis, we have presented a heuristic algorithm to solve the fault tolerant logical topology design problem stated in section 1.3. The logical topology derived using our heuristic may not always be optimal, but we guarantee that it is feasible with respect to the given physical network and can withstand any single physical link failure. For each failure scenario, our algorithm also determines a strategy to route the traffic over the remaining logical edges in such a way that the capacity of a lightpath is never exceeded.

With the growth of WDM technology, potentially hundreds of channels are available in a single fiber. Therefore, wavelengths are no longer scarce resources to be minimized. The cost of transmitters and receivers at each node is becoming the most important factor determining the cost of a network. Consequently, an efficient topology design strategy should try to minimize the number of transmitters and receivers required. This can be achieved by minimizing the number of lightpaths in the network, since each lightpath requires one transmitter and one receiver. This is the objective we have used and our algorithm tries to reduce the number of lightpaths in the logical topology as much as possible.

We have tested our approach on a number of well-known physical networks and compared our results with survivable topologies based on existing path protection schemes. The results demonstrate that our approach is much more efficient in terms of resource utilization.

1.5 Organization Of Thesis

This thesis presents a new approach for fault tolerant logical topology design in WDM optical networks. The remainder of the thesis is organized as follows. Chapter 2 reviews some relevant topics in WDM networks and logical topology design. Chapter 3 presents our heuristic algorithm for fault tolerant logical topology design and also discusses the implementation details of the heuristic. Chapter 4 presents the experimental on some well-known networks. Finally, Chapter 5 contains concluding remarks and directions for future work.

Chapter Two

2.0 Review of Related Techniques and Technologies

2.1 Network Structure

In this section, fiber-optic technology has been described in relation to its use in different networks: access, metropolitan and backbone. Wavelength division multiplexing is, then, introduced.

2.1.1 Today's Communication Networks

The aim of computer networks is to provide communication services in our society. With the growth of internet, the possibility of accessing any information from any corner of the world has been increased, thereby augmenting the human desire to reach this information easily at any time, and with high speed. With the increasing number of population who have access to the internet and with the high availability of bandwidth-intensive applications such as data browsing on the world wide web (www), java applications, video conferencing, interactive distant learning, on-line games etc, the demand for data traffic has been growing exponentially. There is a mismatch between the exponential growth of the data traffic and current high-speed network capability. Consequently, this growth in the data traffic needs to be supported by the current high speed network.

Fiber-optic technology can meet the increasing demand for band width [Muk97]; huge bandwidth (nearly 50 terabits per second), low signal attenuation, low signal distortion, low power requirements and low cost. Due to these characteristics, several networking technologies use fiber as their physical media, such as ATM, SONET, FDDI, and Gigabit Ethernet. Optical network can be best described as follows [BB97]: a telecommunication network with transmission links that are made up of fibers, and with an architecture that is designed to exploit unique features of fibers.

Today's communication networks can be considered to be comprised of three sub-networks: access (covering 1-10 km), metropolitan (covering about 10-100 km), and backbone (extending to 100s or 1000s of km) as depicted in the Figure 2.1. Each of these sub-networks has different set of functions to perform, and therefore, each has a different set of technological requirements and problems.

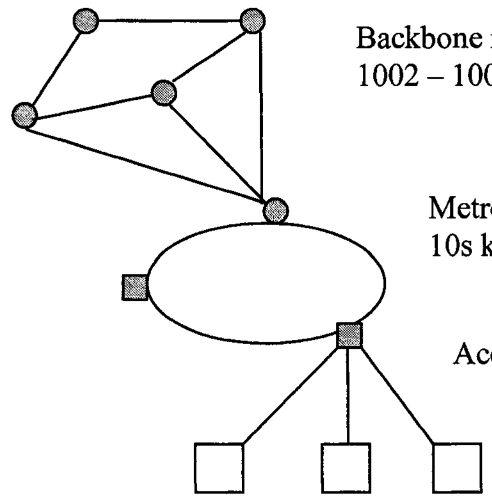


Figure 2.1: Today's communication network structure.

The access network connects the subscriber (home or business) to the service provider. In other words, the access network serves as the last mile (as well as the first mile) of the information flow. It has been concluded in [KP02] that the last mile is becoming the bottleneck in today's network infrastructure. The bandwidth problem in access network can be solved using optical technology since the optical technology can provide 10 to 100 times more bandwidth in compared with its counterpart technologies. Fiber to the building (FTTB) or fiber to the home (FTTH) would be the next development in access network deployment enabling Gigabit per second speeds at cost comparable to other technologies.

Metropolitan area (metro) network connects access networks to backbone networks. Currently, SONET/ SDH based- rings are being used in the physical infrastructure in metropolitan area networks.

The backbone network comprised of optical network nodes interconnected by a mesh of fiber links. Traffic from end users are collected by access network and injected into the backbone network through metro networks. This high bandwidth of traffic is carried on a backbone network from one end to the other by optical communication channels on fibers. Since the scope of this thesis is backbone network, the rest of the section will cover several aspects of optical communication in backbone networks.

2.1.2 Wavelength Division Multiplexing

A fiber's potential bandwidth is 50 Tb per second which is nearly three orders of magnitude higher than electronic data rates. The end user is limited to access the network by electronic speed. Therefore, to exploit the fiber's huge bandwidth, concurrency among multiple transmission channels should be introduced.

Since wavelength-division multiplexing (WDM) supports cost effective method to provide concurrency among multiple transmissions in the wavelength domain, WDM is a favorite multiplexing technology in optical communication networks. A number of communications, each carried by a different wavelength, are multiplexed into a single fiber strand at one end and de-multiplexed at the other end, thereby enabling multiple simultaneous transmissions. Each channel can operate at chosen electronic speeds e.g. OC-192 (i.e. 10 gigabit per second) or OC-768 (i.e. 40 gigabit per second).

2.2 Optical Technology

This section briefly describes the physical layer technology in optical networks which are fiber, amplifier, transceivers, wavelength converter, and switches.

2.2.1 Optical Fiber

Optical fiber is the physical medium for transporting the signals in optical networks. Optical fibers are made up of silica. "Fiber is essentially a thin filament which acts as a wave guide" [Muk00]. An optical fiber consists of a cylindrical core surrounded by a cladding. Fig 2.2 depicts a typical cross-section of a fiber.

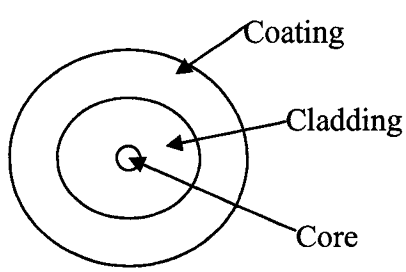


Figure 2.2: Cross section of a fiber.

The principle of propagation of signals in fiber can be explained by simple optics. Fig-2.3 illustrates the reflection principle on a boundary of two materials with different refractive index. Refractive index is the ratio of the speed of light in free space to the speed of light in the medium. If the refractive index of medium 1 is n_1 and the refractive index of medium 2 is n_2, then,

$$\theta_r = \theta_i \text{ ....(0.1)}$$

$$n_1 \sin(\theta_i) = n_2 \sin(\theta_t) \text{ ....(0.2)}$$

Hence, θ_i is the angle of incidence,

θ_r is the angle of reflection, and

θ_t is the angle of transmitted ray.

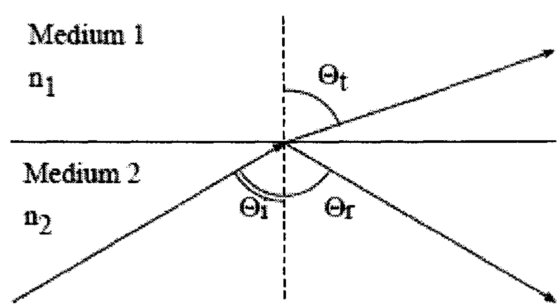


Figure 2.3: Refraction and reflection of a ray. [Dut01]

Equation (2.2) is known as Snell's law. The critical angle for the incidence ray for which the transmitted ray lies on the boundary is

$$\theta_c = \sin^{-1}(\frac{n_2}{n_1})$$

At angles greater than θ_c, the energy of incidence ray is totally reflected resulting in a guided ray. This guided ray carries the optical signals. This situation occurs when the refractive index of cladding is less than that of core (i.e. $n_2 < n_1$).

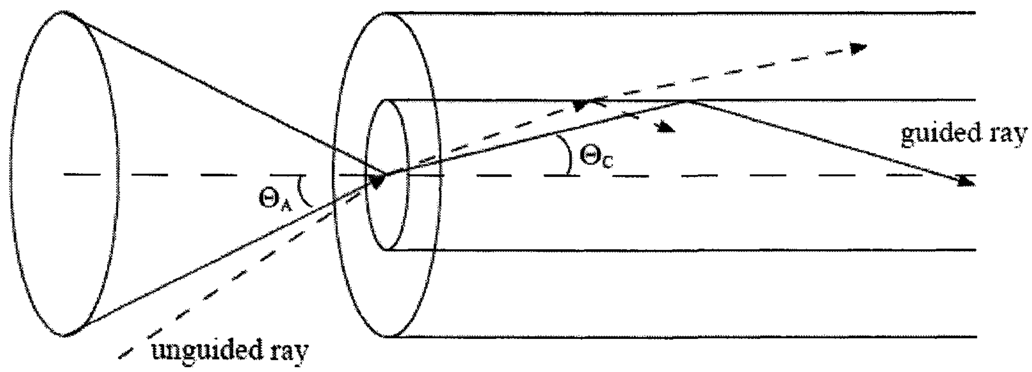


Figure 2.4: Propagation of guided rays in fiber. [Dut01]

The largest angle of the guided ray is the acceptance angle and can be calculated from the following equation if the ray entered from air:

$$\theta_A = \sin^{-1}(\sqrt{n_1^2 - n_2^2})$$

In WDM, the total bandwidth of a fiber is divided into several wavelength channels. Each of these wavelength channels operate at different wavelength. Thus, the number of channels that can exist in a single fiber is limited by the fiber band width and spacing between channels [SB99], [GSM03]. A large number of wavelengths (above 160) are packed into the fiber in dense wavelength-division multiplexing (DWDM). Coarse WDM (CWDM) is an alternative WDM technology with smaller number of wavelengths (less than 10), larger channel width and larger channel spacing.

2.2.2 Signal Amplifiers

Though optical fiber is made from extremely pure silica, a part of light is still lost on its way through the fiber. Therefore, for long transmission, signal amplifiers are required to boast the signal. There are three types of amplifiers which are Semiconductor optical Amplifiers (SOA), Erbium-Doped Fiber Amplifiers (EDFA), and Raman Amplifiers. Among them EDFA can be used for long distance links, such as submarine fibers, placing them every 80 km along the link. The gain of EDFA is 25-51 dB, and its spectral range is 35 nm around 1550 nm. The essential characteristics of lasers which are tunable bandwidth, speed and temperature stability are suitable for WDM networks. A recent technology uses a circuit of EDFA to fully exploit the spectrum of all-wave fiber and it is called ultra wide-band EDFA [Muk00].

2.2.3 Optical Transmitter

The optical transmitter produces the optical signal in the form of a laser (light amplification by stimulated emission of radiation). The laser is a device which converts electrical energy to monochromatic light. In optical network, the semiconductor lasers are used and they are very small in size. In a WDM network, different wavelengths from the lasers and wavelength range in the infrared region, between 1300nm – 1550nm.

2.2.4 Optical Receiver

Optical receivers detect light wave signals and convert them to an appropriate signal for processing by receiving node. As tunable transmitter, there are also tunable receivers and range can be as large as 500 nm.

2.2.5 Wavelength Converter

As the name describes, the wavelength converter converts optical signals at λ_i to a signal at λ_j. To facilitate switching and to prevent blocking due to wavelength unavailability at output fiber, the wavelength converters are used in optical switches.

2.2.6 Optical switches

In a WDM mesh network, the nodes are equipped with optical switches which route the incoming data to their destination nodes. Statistically it has been found that 80% of the traffic arriving to a node has a destination node different from that node. In WDM network, a single fiber potentially carries 50 terabit per second and each node may have hundreds of incident fibers. In such a network, electronic packet switching is impractical because of the processing load and today's electronic processing speed. Therefore, optical switching technology is used in WDM networks to provide efficient and flexible traffic routing.

The simplest optical switch is a 2 x 2 optical coupler. Fig 2.5 shows 2 x 2 optical switches which can be used to build a larger block of switches. This switch has two states, one is bar and the other is cross which is controlled by control signal α. In bar state, signal from I_1 and I_2 are directed to output ports O_1 and O_2 respectively. In cross state, signal from I_1 and I_2 are directed to output ports O_2 and O_1 respectively.

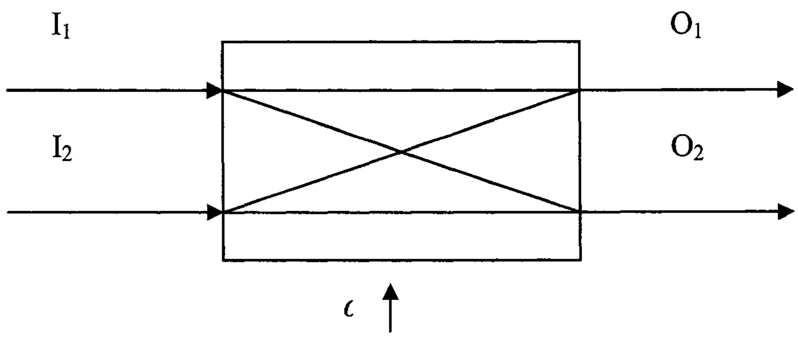


Figure 2.5: A 2 x 2 directional coupler.

A typical optical cross connect (OXC) is shown in fig-2.6 with n-input fibers, each of which carries optical signals in m-wavelengths and are connected to wavelength de-multiplexers which are used to separate the signals on the fibers. Same wavelengths from all input fibers are sent to wavelength specific n x n switch which routes the input signals to appropriate output ports. Using wavelength multiplexers at output port, the signals from switches are multiplexed into a fiber. Total m number of n x n switches are used in the optical cross connect (OXC), one for each wavelength.

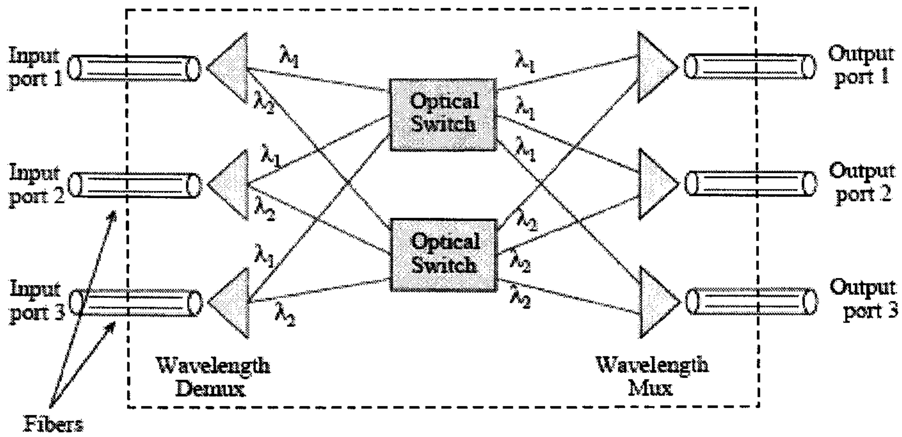


Figure 2.6: 3 x 3 optical cross connect (OXC) with 2 wavelength per fiber. [RP02]

2.4 Design Of WDM networks

The physical topology design comprises of determination of the number of OXCs and interconnection among them. The network configuration problem involves the determination of the size of OXCs, the number of fibers and the set of lightpaths. Routing and wavelength assignment is concerned with the mapping of lightpaths onto the physical topology and assigning wavelength to these lightpaths. In [KA98], general analyses of various formulations and solution approaches to the above problems have been performed.

2.3.1 Design Phases of WDM network

The WDM optical-network design phase consists of three steps:

1. Determination of user demand: In this step user demand has to be measured or estimated. In case of an existing network, user demand can be measured; otherwise, the demand must be estimated from statistical information which includes the expected user population and the expected usage patterns.

2. *Physical topology* design: This phase consists of determining the number and size of OXCs and the fiber links between them.

For physical-topology design, users demand forecast is known and has to decide on a topology to connect client subnetworks through OXCs. This topology design includes the determination of the number of OXCs, the number of wavelength channels and the capacity of each channel as well as the placement of optical components such as amplifiers, wavelength converters, and power splitters. Also to ensure survivability against link or OXCs failure, there should be at least two paths between any pair of OXCs in the network which means that paths should be at least biconnected. There may be some other constraints on physical topology design which includes geographical or administrative considerations.

A physical-topology design problem was considered in [XRP01]. The number of LSRs [KA98] and set of lightpaths to be set up among pairs of LSRs was given, the objective was to determine the two connected physical topology with the minimum number of OXCs to establish all the lightpaths .This was also a combined physical/virtual topology design problem in which the routing and wavelength assignment for the lightpaths was determined. A genetic algorithm was used to iterate over the space of physical topologies and heuristics were established for routing and wavelength assignment on a defined physical topology.

The physical-topology design problem has been gaining attention with the improvement of OXCs. In [BB97] and [BB96], the authors studied relationship between some topology parameters which includes connectivity, nodal degrees, and average hop distance and the number of wavelength needed through simulation. [HRS96] Provided approximate equations for the number of wavelengths, the nodal degree, the total fiber lengths, and the maximum number of transit nodes of a lightpath. [Bea99] carried out analytical solution for routing and wavelength assignment problem for some regular topologies which includes shuffle and tori.

3. ***Logical topology*** **design** (also known as virtual topology design). In this phase, given a traffic demand, a static routing and wavelength assignment problem has to be formulated and solved in order to create lightpaths between client sub-networks to satisfy the traffic demand.

The logical topology design problem can be approximately divided onto four sub-problems [KS98], [RS96]:

1. Topology sub-problem: Define the logical topology to be laid on physical topology that is, determination of the lightpaths.

2. lightpath routing sub-problem : Determine the physical links that each lightpath uses, i.e., route the lightpaths over phusical topology.
3. Wavelength assignment sub-problem: Determine the wavelengths that each lightpath uses, i.e., assignment of wavelength to eash lightpath.
4. Routing sub-problem: Route the traffic between source and destination nodes over the logical lopology.

Optimizing the network resource utilization is the main motivation in logical topology design; other factors include improving network performance and throughput, reducing congestion, delays and so on.

2.3.2 Notation

In this section, we introduce some terminology and concepts that we will be using in the following chapters and common to all logical topology design.

The physical topology [RD00] is represented by a graph in which each node in the network represents a vertex and each fiber optic link between two nodes represents an arc. This arc representation of the graph is commonly known as physical link, or sometimes just a link. Each fiber link is usually bidirectional, therefore the graph is assumed to be undirected. Each physical link is associated with a weight and this weight is usually the fiber distance or propagation delay over the corresponding fiber.

A lightpath [RD00] is defined by a clear optical channel between two nodes in which traffic will not be converted into electronic forms at any intermediate nodes. In lightpath, traffic remains and routed as optical signal throughout. The lightpath represents a sequence of physical links which forms a path from source node to destination node with wavelength continuity constraint and a single wavelength exists for this lightpath which is set on each of these links for this lightpath.

The logical topology [RD00] is represented as a directed graph in which the set of nodes is the same as that of the physical topology graph, and each lightpath is an arc. An example of logical topology for a fixed physical topology is depicted in figure 2.7.

Physical topology ——

Logical topology ——

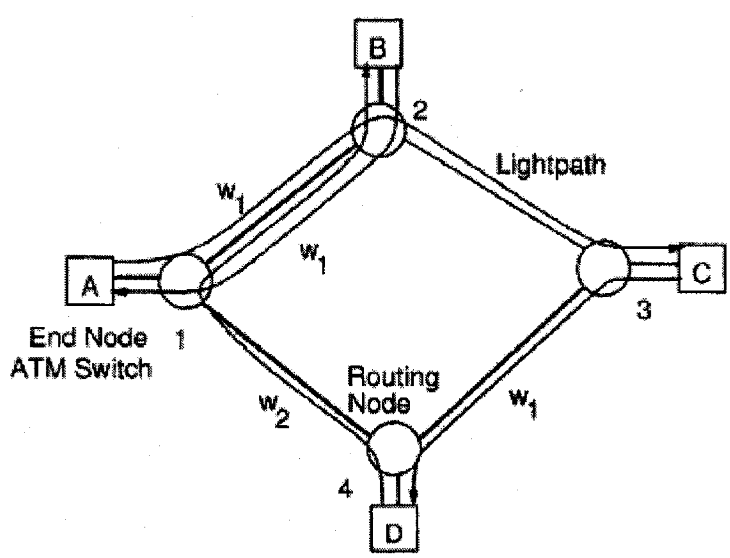


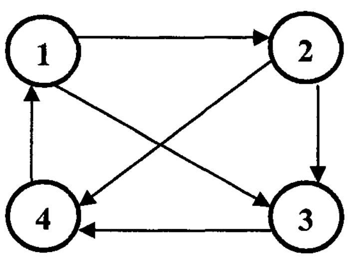
Figure 2.7: Logical and Physical topology. [RS96]

Wavelength continuity constraint: In a WDM network, end users communicate with each other through all-optical channels which are also known as lightpaths. Lightpaths are used to support connection and may span multiple fibers in a WDM network. If wavelength converters are absent in the network, a lightpath must use the same wavelength throughout the path it traverses; this property is known as wavelength continuity constraint [Bra90].

Routing and wavelength assignment (RWA): A logical topology in a WDM optical network is made up of lightpaths or logical links and in absence of wavelength converter, a lightpath must occupy the same wavelength on all fiber links it traverses. Given a set of connections, the problem of setting up of lightpaths and assigning wavelengths to each of these lightpaths is known as Routing and Wavelength Assignment (RWA) problem [ZJM00].

Typically, connection requests can be of three types: static, incremental, and dynamic [ZJM00]. In static traffic case, the entire set of connections are known in advance and the problem is then setting up of lightpaths for these traffic with the objective to minimize the network resources, such as, number of wavelengths or number of fibers in the network. With incremental traffic, connection request arrives sequentially, a lightpath is then setup for each connection and the lightpath remains in the network indefinitely. In dynamic traffic, a lightpath is setup for each connection request as it arrives, and the lightpath is released after a finite amount of time. Minimizing the number of connection blocking or maximizing the number of connections that are established in the network at any given time is the objective of incremental and dynamic traffic case. The RWA problem for static traffic is known as the static lightpath establishment (SLE) problem. The RWA problem for incremental and dynamic traffic is known as dynamic lightpath establishnment (DLE) problem.

Traffic Matrix specifies average amount of data to be transmitted between each pair of nodes in the network [6]. If there are N nodes in the network, the traffic matrix is a square matrix N x N and denoted by $M = [t^{(sd)}]$, where $t^{(sd)}$ is the average traffic from node s to node d.



Logical topology

(a)

Node	1	2	3	4
1	0	15	5	10
2	0	0	28	32
3	0	16	0	75
4	55	25	20	0

(b)

Figure 2.8: 4-Node logical topology and corresponding traffic matrix.

Figure 2.8(a) illustrates an example of a logical topology of WDM network with 4 network nodes and 2.8(b) shows the corresponding traffic matrix. The diagonal of the traffic matrix is zero since no traffic can flow to and from same node. The average traffic is being expressed as a percentage of capacity of a single lightpath. From the above traffic matrix we can see that traffic from node 1 to node 4 is 10% of the capacity of the lightpath. Consequently, if the capacity of lightpath is 2.5 Gigabit per second, then the traffic from node 1 to node 4 is 0.25 Gigabits per second.

2.4 Survivability in Optical Networks

Today's optical network is a layered architecture. The WDM layer is considered to be the lowermost layers and it supports other higher layer services, such as SONET connections, ATM virtual circuits and IP-Switched datagram traffic. Figure 2.9 shows the layered architecture and lightpath transmission between electronic layer and optical layer.

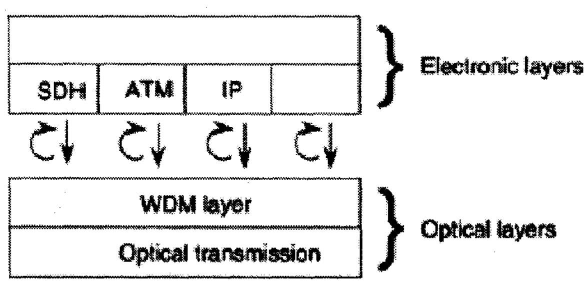


Figure 2.9: Layered Architecture and Lightpath provisioning in WDM network. [MPPM02]

Higher layers may or may not have recovery mechanisms in the protocol. Because of this reason WDM layer should be capable of providing all the survivability techniques. Survivability at WDM layer cannot protect against failure in higher layers. However, WDM layer protection still offers some advantages over protection at higher layers [EN01], [ZS00], which includes

Speed: Recovery time at WDM layer is faster as it does not have to wait for the signals from any other layer.

Simplicity: The survivable mechanisms need less co-ordination than recovery schemes at higher layer.

Transparency: The wavelength routing protection technique is not dependent on the protocols used in higher layers.

2.4.1 Survivability Techniques in Optical Network

There are several approaches and schemes that have been introduced for optical network survivability in past few years [ACL97], [ZS00], [GR00b], [RM99], [Wu95], and [Wu92]. Survivable architecture in optical network can be categorized into two different types: pre-designed protection and dynamic restoration [ZS00]. Survivability techniques for different network architectures are shown in figure 2.10.

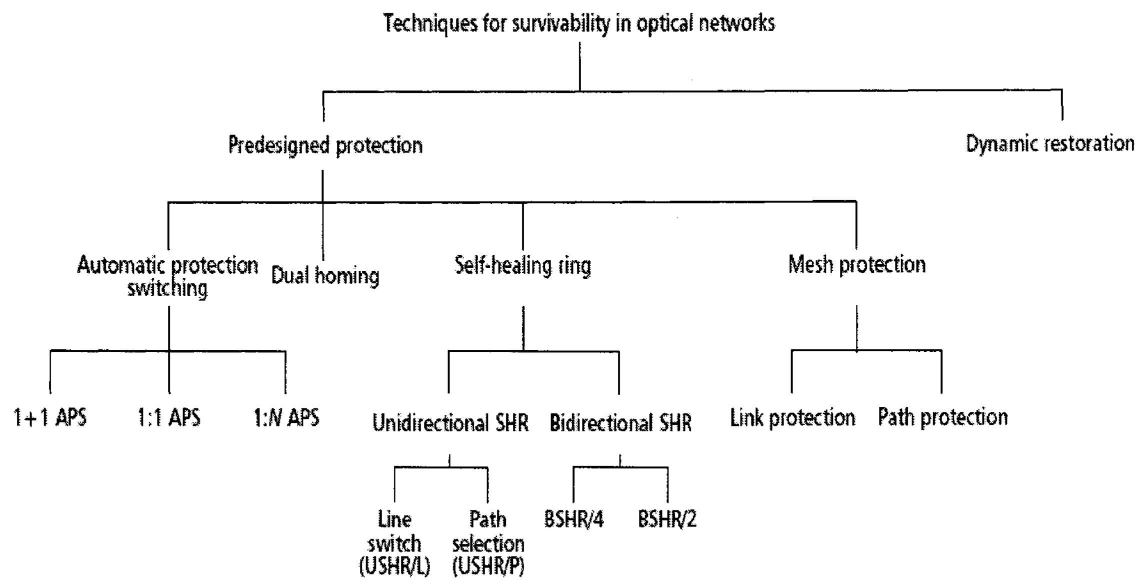


Figure 2.10: Survivability Techniques for optical networks. [ZS00, pp. 2]

The definition and explanation of each scheme is given below:

2.4.1.1 Dynamic Restoration

In this scheme, free resources are searched dynamically in the network to restore the affected services when network failure occurs. Therefore, the resources are not reserved at the connection set up time, which make this scheme economical over predesigned protection approach.

2.4.1.2 Automatic Protection Switching

APS technique is useful for link failure optical network. There are three architectures for this type of protection scheme. The difference among three architectures is the assignment of protection resources [ZS00].

1 + 1 APS: A protection link is dedicated for every working link. The source node sends the information on both working and protection links. At the receiver side the better information is accepted, even in case of failure, the destination is able to receive the signal.

1:1 APS: For every working link there is one protection link but the protection link is used only when a failure happens. In all normal cases they remain idle.

1: N APS: In this scheme, N working links share a single protection link.

2.4.1.3 Self-Healing Ring (SHR)

The BSHR architecture can be of two and four line fiber protection schemes.

2.4.1.4 Mesh Protection

This scheme is classified into link-based protection and path-based protection. Detailed discussion on these approaches will be found in the next section.

2.5 Survivability of WDM Mesh network

Mesh network architecture is becoming more important in WDM technology because of the tremendous development of the OXCs. Compared to ring architecture, mesh topology is more critical in terms of survivability issues as it has higher number of routing and design decision to consider [MPPM02]. Much Research has carried out on survivable WDM mesh topology and most studies consider single link failure [AA99] [SS92], [FDS04], and [SSM03] studied the survivability of WDM mesh networks due to dual-link failure. [ZZM04] examines survivability of WDM mesh networks due to multiple link failure using backup reprovisioning technique. In [ZM04], Jing Zhang and Biswanath Mukherjee reviewed basic concepts and fault management in WDM mesh networks. [FS03] Discussed 5 protection schemes for preplanned recovery in WDM networks. The state-of-the-art progress and reported research on the WDM mesh networks has been summarized in [HM04]. In [OZZS+04] and [OZZS+03], authors proposed approaches for shared path protection in WDM mesh networks. [EHS00]

Discussed protection cycles in WDM mesh networks. The reader is referred to [NM02] for network architectures supporting survivable WDM networks.

Different schemes for surviving single link failure are given in the figure 2.11.

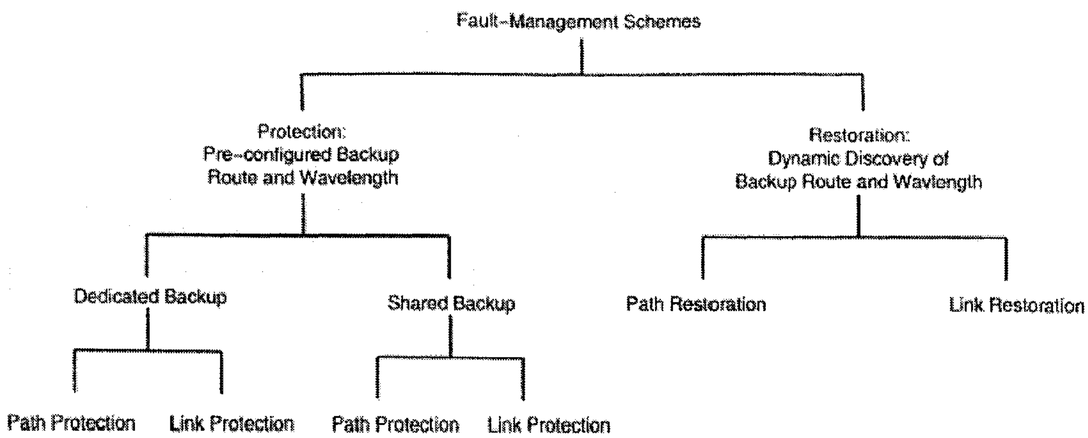


Figure 2.11: Different schemes for surviving link failure. [RM99, pp. 2]

2.5.1 Path Protection

The main idea of path protection is to have a working (primary) and protection (backup) lightpaths at the time of connection set up. The protection paths do not traverse the failed link. In the figure 2.12, the working path from node 1 to node 6 is 4-5-6. When the link 5 -> 6 fails, the connection goes through protection path 4-1-2-6, avoiding the failed link.

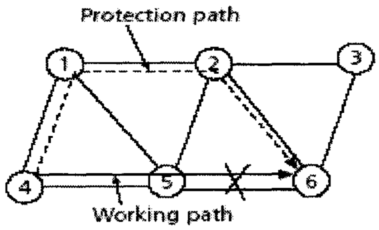


Figure 2.12: Path Protection Technique. [ZS00, pp. 6]

The wavelengths in protection path and working path can be same or different.

2.5.1.1 Dedicated Path Protection

In this scheme, a connection will have dedicated resources along its back up path and these resources will not be shared with the backup paths for other connections [RS02]. For example, figure 2.13 has two working paths, 4-5-6 and 1-2-3 both are using λ_1. The protection wavelength path for connection 1 is λ_2 on 4-1-2-6. The protection path for connection 2 is 1-5-2-6-3. Both the paths have a common link 2-6. And since λ_2 has been assigned to path 1; protection path 2 must be assigned a different wavelength.

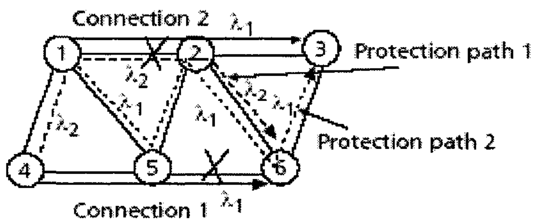


Figure 2.13: Dedicated Path Protection. [ZS00, pp. 6]

2.5.1.2 Shared Path Protection

Shared path protection is similar to dedicated path protection, however in case of shared path protection; the backup wavelength reserved on the links of the backup path may be shared with other backup paths. This allows multiplexing of backup channels among different failure scenarios not occurring simultaneously. Therefore, shared-path protection is more capacity efficient than dedicated-path protection. The two backup paths can now share λ_2 on the link 2-6 in figure 2.14. Thus, only one wavelength on this link has to be reserved for protection.

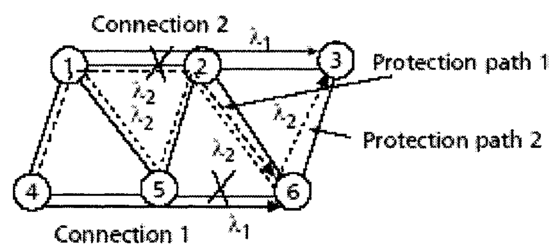


Figure 2.14: Shared Path Protection. [ZS00, pp. 6]

2.5.2 Link Protection

In link protection all the connections are rerouted around the link which has failed. As illustrated in the figure 2.15, if the primary link between nodes 2 and 3 fails, a backup path 2-4-5-3 would be used for rerouting. The source and destination nodes are unaware of the link failure.

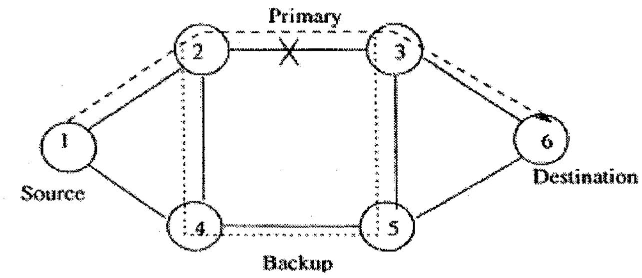


Figure 2.15: Link Protection. [RM98, pp. 3]

2.5.2.1 Dedicated Link Protection

In the dedicated link protection at the time of call setup for each link of the primary path a backup path and a wavelength are reserved around that link, and are dedicated to that call. In figure 2.16, let λ_1 on path 5-2-6 be the protection wavelength path for a working channel on link 5-6, and the protection path for a working channel on link 1-2 is 1-5-2. Then, a different wavelength λ_2 must be assigned to protection path 2, even if the working wavelengths on links 5-6 and 1-2 are the same, say λ_1.

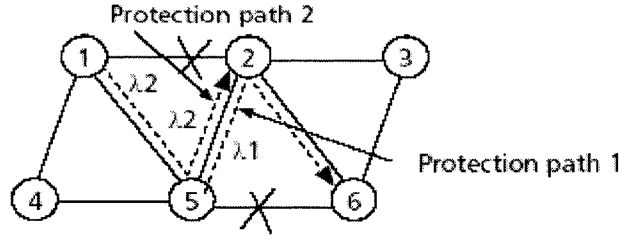


Figure 2.16: Dedicated Link Protection. [ZS00, pp. 5]

2.5.2.2 Shared Link Protection

At the time of call setup for each link of the primary path, a backup path and wavelength are reserved around that link. The backup wavelength reserved on the links of backup paths may be shared with other backup paths, resulting in multiplexing of backup channels among different failure scenarios that don't occur simultaneously. Therefore, shared-link protection is more capacity efficient than dedicated link protection. Figure 2.17 shows the shared link protection on link 5-2 for wavelength λ_2.

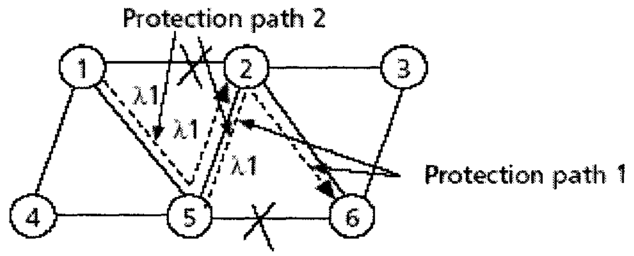


Figure 2.17: Shared Link Protection. [ZS00, pp. 5]

Chapter Three

3.0 A Heuristic for Fault Tolerant Logical Topology Design

In this chapter, we describe our approach for designing a survivable logical topology. The logical topology, generated using our approach, always has a survivable routing. In other words, the logical topology remains connected for all possible single link failures. Furthermore, we guarantee that the surviving topology is not only connected, but is capable of handling the entire traffic demand for all single link failure scenarios. In this chapter, we first define the WDM network model used in our research, which includes physical topology, the fiber characteristics, and the traffic matrix. Then, we discuss the objectives of our algorithm and finally we give a detailed description of our strategy for designing a survivable logical topology.

3.1 WDM Network Model Definition

The WDM network model used in our design is a mesh topology comprised of a number of end nodes, a number of router nodes and a number of physical links connecting two nodes (end nodes or router nodes). Each link between nodes i and j is bidirectional and consists of two unidirectional fibers. We assume that the capacity of each fiber (i.e. the number of WDM channels available on the fiber) and the capacity of a single WDM channel (i.e. the maximum amount of traffic it can carry) are the same for all fibers. We are given the following information about the current state of network:

- A physical fiber network G [**N, E**] with $|\mathbf{N}| = N$, and $|\mathbf{E}| = m$.

- A set of channels **K** that each fiber can accommodate, with $|\mathbf{K}| = K$.
- A set of R edge-disjoint paths, over the physical topology, between each source-destination pair. In this paper, we have used $R = 3$.
- A set of potential logical edges (lightpaths) P. We assume that there is one potential (directed) logical edge from each source s to each destination d, so $|P| = N(N\text{-}1)$.
- $d^{e}_{pr} = 1$, if and only if the r^{th} physical route for the p^{th} potential lightpath uses link e.
- A set of commodities Q. If there is a non-zero traffic requirement from a source node s_q to a destination node d_q, then this source-destination pair to correspond to a commodity $q \in Q$.
- s_q (d_q) = the source(destination) node for commodity q.
- A traffic demand matrix T = (t_q), where t_q is the amount of traffic corresponding to commodity $q \in Q$. We assume that t_q is expressed as a percentage of the capacity of a lightpath.

3.2 Objective

Given the physical topology and the traffic matrix, the goal of our study is to determine a set of lightpaths to handle all the traffic communication requirements specified by the traffic matrix such that i) the cost of the network minimized, ii) the resulting logical topology remains connected and is capable of handling all single physical link failure scenarios, and iii) a feasible RWA can be determined for the set of lightpaths, over underlying physical topology.

The cost we are trying to minimize, in this thesis, is the total number of lightpaths. Since each lightpath requires one transmitter and one receiver, this is equivalent to minimizing the cost of transmitters and receivers. With current WDM technology, it is possible to have close to a hundred channels per fiber. Therefore, the transceivers are becoming the scarce resources to be optimized.

3.3 Heuristic for Logical Topology Design

The first step in our design process is to use a heuristic to design an initial logical topology, which is capable of supporting the required traffic under fault-free conditions. Then this initial topology is augmented by considering each potential single link failure. A preliminary version of the heuristic to create the initial topology was presented in [Hou03]. The inputs required by the heuristic and the outputs generated are listed below.

Inputs:

- A bi-connected physical topology [*N, E*]
- Traffic matrix T
- An initial set of logical edges(normally empty when the design process starts)

Outputs:

- A set of lightpaths which is capable of handling the entire traffic.
- A feasible route and wavelength assignment for the set of lightpaths.

We have modified the original algorithm given in [Hou03], and will give an overview of the modified algorithm in this section. In this algorithm, we use a greedy heuristics which considers each commodity $q \in Q$, in turn, and tries to route the corresponding traffic from s_q to d_q. The commodities are considered in decreasing order of the traffic demand t_q, i.e.

we try to route the traffic corresponding to the highest value of t_q first. When routing the traffic for a given commodity q, the objective is to route the traffic t_q from s_q to d_q, in such a way that the cost (i.e., number of new lightpaths created) is minimized. If the traffic can be routed using spare capacity on existing lightpaths only, then the cost for routing t_q is 0. Otherwise, if l_q new lightpaths must be created, then the cost is l_q. For example, suppose t_q is routed using the multi-hop route: $s_q \rightarrow a \rightarrow b \rightarrow d_q$. If $s \rightarrow a$ and $b \rightarrow d_q$ are the new lightpaths and $a \rightarrow b$ is an existing lightpath, then, total cost to transmit traffic t_{sd} is (1+0+1) = 2. Figure 3.1 shows the steps required to create the initial topology.

Step1: Create, if possible, R edge-disjoint shortest paths for all the $N(N-1)$ node pairs using Dijkstra's algorithm (in our implementation we used $R = 3$).

Step2: T_1 = Sorted list of traffic demands in descending order.

Step3: t_q = first entry in T_1

Step4: While (t_q!= 0), repeat steps 5 – 9.

Step5: If traffic t_q can be routed from node s_q to node d_q using existing lightpaths, update traffic on appropriate edges and Go To Step 9.

Step6: $LT_1 = searchBestPath(N, E, LT_{init}, t_q)$

Step7: If (LT_1== [ ]) STOP and report failure.

Step8: $LT_{init} = LT_1$

Step9: t_q = next entry in T_1

Step10: Return (LT_1).

Figure 3.1: Overview of createTopology function.

In step 1, we create R edge-disjoint shortest paths for each node pair (i, j). In step 2, we sort the entries of the traffic matrix in descending order. Only non-zero entries are considered in steps 4-9. In step 4, we start with the highest traffic entry and consider each non-zero entry in turn. Step 5 checks the spare capacity in the existing lightpaths to see if it is possible to handle traffic t_q using existing lightpaths only. If a sequence of existing lightpaths from s_q to d_q can be found such that each lightpath in the sequence has a spare capacity of at least t_q, then the traffic for commodity q is routed using these existing lightpaths. Such a sequence if lightpaths from s_q to d_q is called a *chain* for commodity q. If no usable chains are found for commodity q, in the current topology, we try to route the traffic by adding some new lightpaths. The cost for routing traffic t_q is the number of new lightpaths that were added to the current topology in order to handle t_q. The function *searchBestPath* is responsible for finding a minimum cost chain for t_q and is described in the detail in section 3.3.2. In both step 5 and step 6, we make the simplifying assumption that the entire traffic t_q from the source s_q to the destination d_q is handled using one chain only. In other words, the traffic for a single commodity is always routed over a single logical path and is not split over multiple paths. If such a chain cannot be found, then the algorithm fails.

3.3.1 Create Shortest Paths

In the ***createTopology* function**, the first step is to find three edge-disjoint shortest paths for each source-destination pair in the network. These edge-disjoint paths are created by successively applying Dijkstra's algorithm [KS98] to each node pair. After finding a shortest path for a particular source-destination pair, we delete the edges used by this shortest path from the physical topology. We then use this modified topology to find next shortest path. This process is repeated until R shortest paths are found. The reason for this step is that, when we create a new lightpath from node i to node j, then we can use one of these R paths to route the lightpath. It is much more efficient to check the R pre-defined paths, than to search all possible paths in the physical network. Using R distinct routes also offers more flexibility than only considering the shortest route. If we are unable to assign wavelength to any one of these paths, we use next shortest path. This provides greater flexibility in routing and wavelength assignment for a particular source-destination pair and usually keeps the path lengths small. Therefore, using R edge-disjoint routes is a reasonable trade-off between searching all possible paths and using only the shortest path. A brief description of Dijkatra's algorithm and an example of creating three edge-disjoint shortest paths is given in [41].

3.3.2 Creating a Minimum Cost Chain

Once we have created three edge-disjoint shortest paths for every source-destination pair, the next step is to sort traffic matrix in descending order. After sorting traffic matrix, we take the current highest traffic entry in the traffic matrix, and try to route the traffic t_q using the existing lightpaths which have already been set up to serve previous requests. For the first (overall highest traffic) entry, there will be no existing lightpaths since this is the first request. For the subsequent requests, we will have some existing lightpaths. Now, say we want to route t_q which is the traffic request for commodity q. To do so, we need to select the logical edges which have spare capacity of at least t_q along the path from the source s_q to the destination d_q. If we cannot reach destination d_q using these selected logical edges, we try to create new logical edges. Each new logical edge that we consider is a potential candidate to be included in the final logical topology. A potential new logical edge will be included in the final topology if and only if that logical edge appears in the minimum cost path from the source s_q to the destination d_q.

Figure 3.2 shows our implementation of the function *searchBestPath*, to find the best route from the source s_q to the destination d_q to accommodate traffic t_q, for a particular commodity $q \in Q$. This corresponds to step 6 in Figure 3.1. *searchBestPath* is an iterative algorithm. In this algorithm, N_v is the set of all previously visited nodes. At the beginning of the r^{th} iteration ($r > 1$) N_v is the set of *all* nodes which can be reached from the source s_q, with a cost of at most $r-1$, and N_0 is the new set of nodes which were reached by a adding a new lightpath in the previous iteration. In step 3, we add new nodes to the set N_0, such that it is possible to reach these new nodes from the current nodes in N_0, using existing lightpaths only. In step 6, we calculate N_1, which is the set of nodes that can be reached from the nodes in N_0, by creating exactly one new lightpath. In the r^{th} iteration, the cost for reaching a node $j \in N_1$ from the source node s_q is r. If the destination d_q is found in either N_0 or N_1, the search is successful. Otherwise, if N_1 is not empty, the search continues to the next iteration. If N_1 is empty, the search fails and an appropriate error message is generated. If the destination node d_q is found in step 7, we calculate the minimum cost route from s_q to d_q (step 9a), and create a new logical topology (LT_{new}) by adding all *potential* edges on this route to the initial topology LT_{init} (step 9b in Figure 3.2). We also adjust the traffic on any existing edges in the minimum cost route by the proper amount. The *searchBestPath* function returns the new logical topology, if the search is successful. If the search fails, the function returns an empty topology, indicating failure.

Step1: Initialize parameters

- $N_0 = \{s_q\}$
- $N_v = \{s_q\}$
- *route-found* = *false*
- *search-failed* = *false.*

Step2: While (*route-found* = *false*) and (*search-failed* = *false*) repeat steps 3-8

Step3: $N_0 = N_0 \, U \{j| \mid j \notin N_v$, and it is possible to route the required traffic from a node $i \in N_0$ to node j, using spare capacity on existing lightpaths

Step4: $N_v = N_0 \cup N_v$

Step5: If ($d_q \in N_0$) then *route-found* = *true.*

Step6: Else $N_1 = \{j| j \notin N_v$, and it is possible to establish a lightpath from a node $i \in N_0$ to $j\}$.

Step7: If $d_q \in N_1$ then *route-found* = *true*

Step8: If (N_1 is *empty*) then *search-failed* = *true.*

Else

a. $N_v = N_0 \cup N_1$

b. $N_0 = N_1$

Step9: If (*route-found* == *true)* then

a. Calculate minimum cost route from s_q to d_q

b. LT_{new} = *setupLightpaths*(LT_{init})

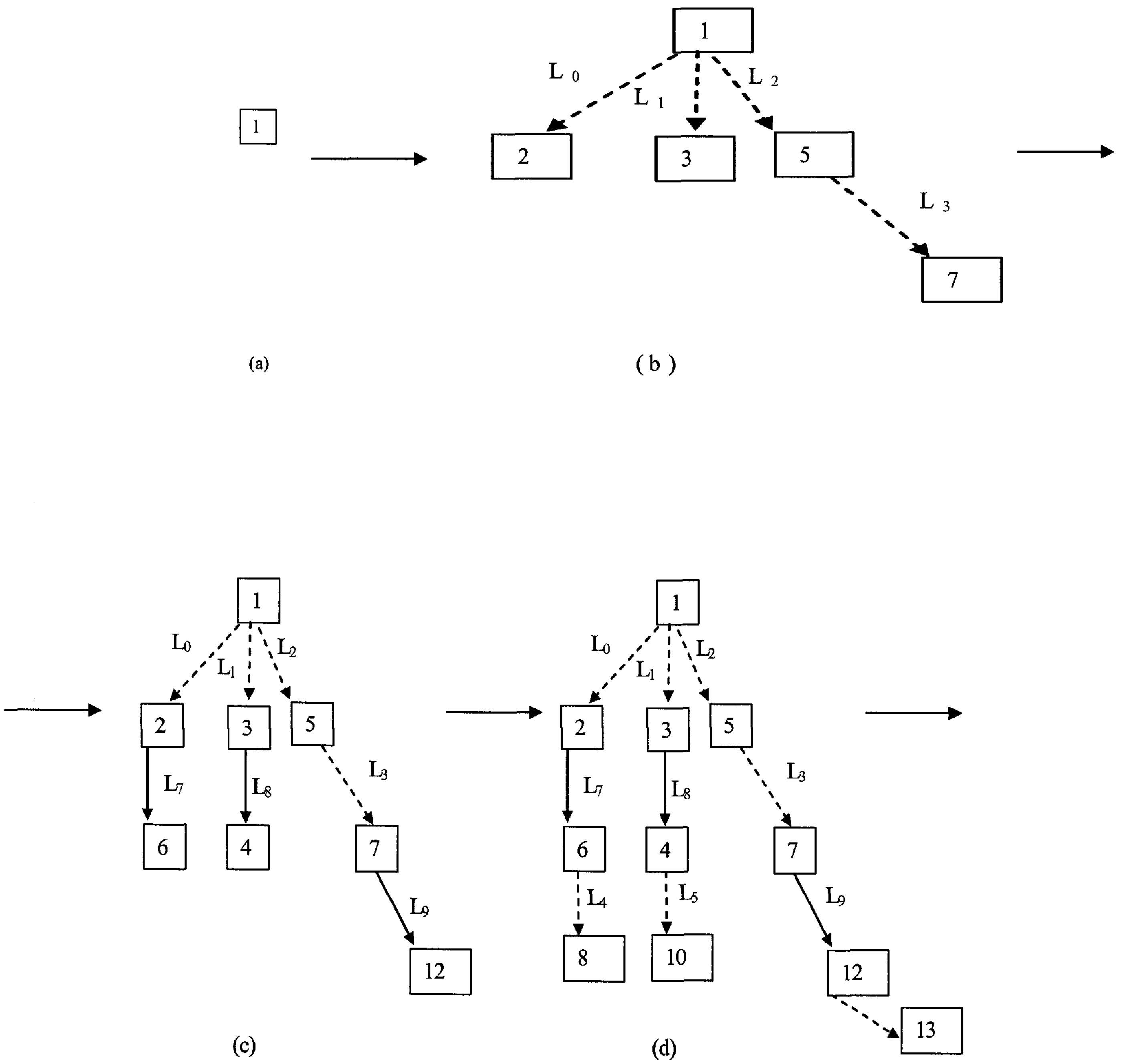
c. Return (LT_{new})

Else Return ([]) /* indicating failure */

Figure 3.2: *searchBestPath* algorithm.

Now we will walk through an example to find a route from the source node 1 to the destination node 14 for a traffic request t_{1-14}.

The set of lightpaths that currently exist in the network is $\{L_0$: $1 \to 2$; L_1: $1 \to 3$; L_2: $1 \to 5$; L_3: $5 \to 7$; L_4: $6 \to 8$; L_5: $4 \to 10$; L_6: $12 \to 13\}$. At the beginning, N_0 contains only source node 1 (Figure 3.3(a)), and the one-cost list is empty. Let the lightpaths L_0, L_1, L_2, and L_3, have the spare capacity at least t_{1-14}. Then, after step 3, $N_0 = \{1, 2, 3, 5, 7\}$, which can be reached using lightpaths L_1, L_2, L_3, and L_4. Figure 3.3(b) shows this situation in which dashed lines are used to depict existing lightpaths. Since node 14 is not in zero-cost list, we go to step 6. Suppose, we are able to establish the following logical edges L_7: $2 \to 6$; L_8: $3 \to 4$; L_9: $7 \to 12$. Figure 3.3(c) depicts this situation in which solid lines represent new logical edges. Now, after step 6, $N_1 = \{4, 6, 12\}$. Since the destination node 14 is not in N_1, we replace N_0 by N_1 (step 8), and go back to step 3. After step 3 is completed, $N_0 = \{4, 6, 8, 10, 12, \text{and } 13\}$, because nodes 8, 10, and 13 are reachable using logical edges L_4, L_5, and L_6 (this situation shown in figure 3.3(d)). Since the destination node 14 is not in the list, we go to step 6. Suppose we are able to set up the following logical edges L_{10}: $8 \to 9$, L_{11}: $10 \to 11$, L_{12}: $13 \to 14$ (Figure 3.3(e)). After step 6, $N_1 = \{9, 11, 14\}$. Since the destination node 14 is in N_1, we go to step 9 and set up the new logical edges required to reach the destination node 14. Therefore, the traffic from node 1 to 14 goes through five logical edges: $1 \to 5$ (existing), $5 \to 7$ (existing), $7 \to 12$ (new), $12 \to 13$ (existing), and $13 \to 14$ (new). The new logical edges required are $7 \to 12$ and $13 \to 14$.


1
2
3
5
7
L_0
L_1
L_2
L_3
L_4
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4
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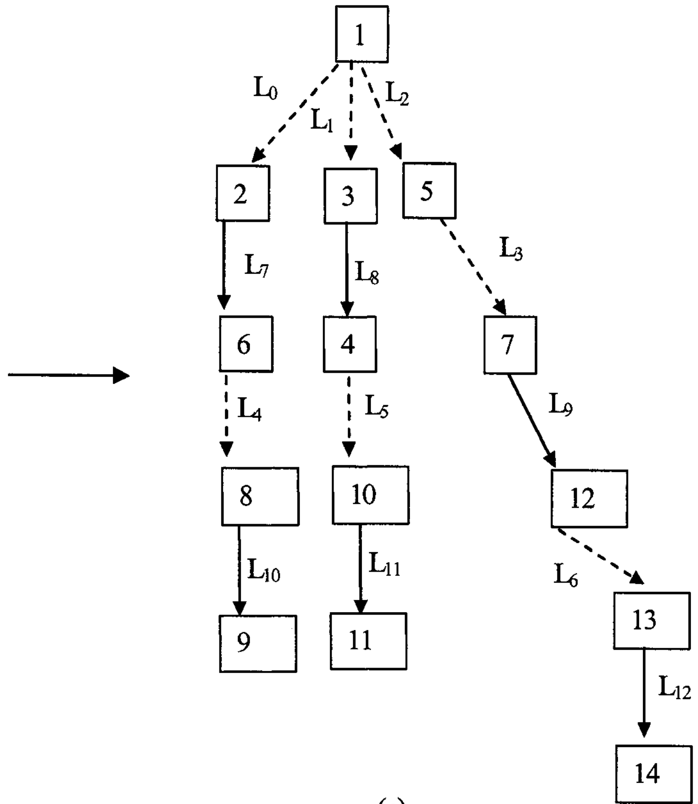
(c)
(d)



(e)

Figure 3.3: An Example for the searchBestPath algorithm.

3.3.2.1 Reuse of Existing Logical Edges

The aim of step 3 of the *searchBestPath* algorithm is to find all new nodes that are reachable from a given set of nodes. To carry out this objective, we first check all the logical edges whose sources are already in the set N_0. We, then, select only those edges whose spare capacity is at least t_q. The destinations of these logical edges are then added to N_0. This process is repeated with the new set of nodes until no new nodes can be added.

3.3.2.2 Create New Logical Edges

In step 6 of the *searchBestPath* algorithm, we create new *potential* logical edges to find a path from the source s to the destination d to accommodate the traffic t_q. A potential logical edge is one which *may* be included in the logical topology. Once the minimum cost route for the current traffic demand t_q has been determined, all potential logical edges which are on the selected routed are added to the final topology. Other potential edges, which are not on the selected route, are deleted and the resources which were temporarily reserved for them are released. Each potential logical edge is from a node $i \in N_0$ to a node j, $j \notin N_v$ (step 6 in Figure 3.2). In other words, the destination j of the new lightpath must be a node which has not been previously visited in the search process.

Before creating a potential edge, we determine whether or not a feasible RWA for the proposed edge exists. In order to do this, we need to know the wavelength information on all fiber links, i.e., which wavelengths are available, and which ones are being used. The wavelength information of *existing* logical edges is readily available. However, we also need to consider the route and wavelength of some the *potential* edges as well. This is because we have to explore a number of possible chains from the source s_q to the destination dq in order to find a minimum cost multi-hop route. Consequently, the route from the source s_q to the current node i has to be taken into consideration where i is the source of the new logical edge. For instance, in figure 3.3(e), when we try to find a new logical edge from node 13, in addition to the existing logical edges, we also need the wavelength information of the new logical edge L_9: $7 \rightarrow 12$, which lies on the route from source node 1 to destination node 14. The wavelength information corresponding to the other potential logical edges such as L_7: $2 \rightarrow 7$, L_8: $3 \rightarrow 4$, L_{10}: $8 \rightarrow 9$ are not relevant at this point due to the fact that they are not on the path $1 \rightarrow 5 \rightarrow 7 \rightarrow 12 \rightarrow 13 \rightarrow 14$. This means they will never be created if the traffic follows the route $1 \rightarrow 5 \rightarrow 7 \rightarrow 12 \rightarrow 13 \rightarrow 14$. A potential edge is only created if there is a feasible RWA for that edge.

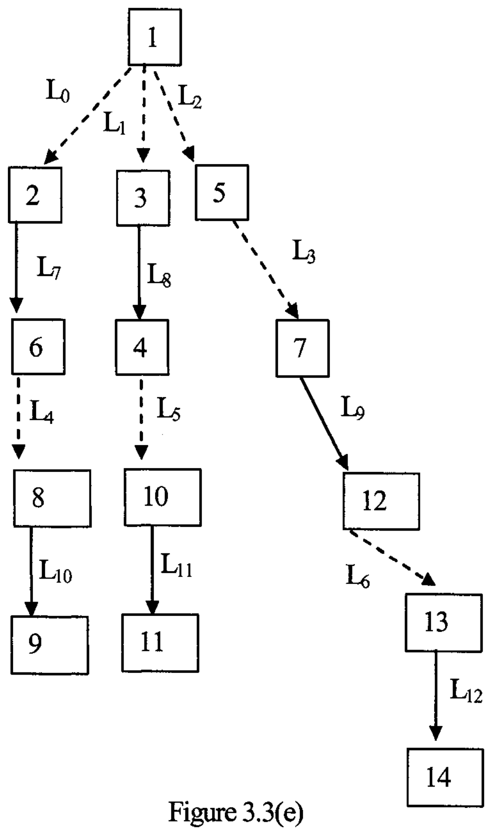


Figure 3.3(e)

To determine if it is possible to establish a lightpath between a source-destination pair (i,j), we have to

- Find a route for the lightpath
- Assign a wavelength λ_m to that lightpath

If this is successful, then we can establish a new logical edge from node i to node j. The function *findRWA* is responsible for finding a physical route and wavelength for the potential logical edge. An outline of the function is shown in figure 3.4. If an available wavelength on one of the pre-defined physical routes can be found, then the function returns the assigned wavelength. Otherwise, it returns a value of -1, indicating failure

Step1: Initialize

a. *assigned-wavelength* = -1

b. $r = 0$

Step2: while ($r < R$) and (assigned-wavelength == -1) {

Step3: $p_{ij} = r^{th}$ pre-computed shortest path p from i to j

Step4: For each edge e in p_{ij}

a. Λ_e = set of available channels on link e

Step5: $\Lambda = \bigcup_{e \in p_{ij}} \Lambda_e$

Step6: If ($\Lambda \neq empty$) then assigned-wavelength = any $\lambda \in \Lambda$

}

Step7: Return (assigned-wavelength)

Figure 3.4: Overview of findRWA function.

3.3.2.3 Set up New Lightpaths

This corresponds to step 9 of the searchBestPath algorithm. In this step, the new lightpaths in the minimum cost chain for commodity q are actually set up. A new lightpath may span multiple physical edges. This information along with the wavelength information is saved for easy retrieval later. If an existing lightpath is used for handling traffic t_q, then we reduce the capacity of the lightpath by the amount t_q. Finally, the chain (i.e. sequence of logical edges) used to route the traffic for commodity q is also saved in a table called the *commodity table* [Appendix C].

3.4 Fault Tolerant Topology Design

In this section, we outline our heuristic for creating a logical topology which can support the entire traffic demand for any single link failure. The first step in our design process is to design an initial logical topology, which is capable of supporting the required traffic under fault-free conditions. Then this initial topology is augmented by considering each potential single link failure scenario. An overview of our algorithm is given in Figure 3.5

In step 1, the function *createTopology* is used to design the initial topology LT_0. This function takes as input an underlying physical topology (consisting of the set of nodes N and the set of physical links E), a set of traffic requirements T, and an initial logical topology LT_{init} (specified by the set of lighpaths already established). The set LP_{init} is empty when the design process first starts. *createTopology* generates a new logical topology i.e., set of new logical edges LT_{new}, which is capable of handling the traffic requirements in T and has a feasible RWA over G= [**N, E**].

In steps 3 – 9, we consider, we consider a specific failure scenario, and augment the current topology, by adding new lightpaths to handle the disrupted traffic. In step 3, we update the physical topology by removing the faulty link e. In step 4, we calculate the set of lightpaths LP_f that are affected by failure of link *e*. In other words, LP_f includes those lightpaths that traverse link *e*. In step 5, we create a temporary logical topology by removing the affected lightpaths from LT_0. In step 6, we calculate the disrupted traffic for each commodity $q \in Q$, and create a new traffic demand *T'*.

1. LT_0 = CreateTopology (*N, E, T,* [ ])

2. For each $e \in E$ {

3. $E' = E - \{e\}$

4. LP_f = set of lightpaths in LT_0 which traverse link *e*

5. $LT_1 = LT_0 - LT_f$

6. $T' = \{t_{q'} | \, t_{q'}$ is the disrupted traffic for commodity $q\}$

7. For each $q \in Q$ {

a. C_f = set of disrupted chains for commodity *q*

b. For each chain $c \in C_f$

c. f_q = amount of flow of commodity *q* on chain *c*

d. reduce traffic on surviving edges of *c* by f_q

}

8. *new-lps* = *createTopology*(*N, E', T', LT*$_1$)

9. If (*new-lps* == [ ]) STOP and report failure.

Else LT_0 = updateTopology(LT_0, *new-lps*)

}

Figure 3.5: Overview of fault tolerant topology design heuristic.

In step 7, for each commodity q, we calculate the set of chains (C_f), which are disrupted due to failure of link e. Here, a chain for commodity q is a sequence of logical edges from s_q to d_q, which carries a flow f_q. A disrupted chain is one which contains at least one lightpath in LP_f. For each surviving logical edge in a disrupted chain, we reduce the traffic by the amount of flow f_q on the chain, under fault-free conditions. This increases the spare capacity on surviving lightpaths, which may be used to re-route some of the disrupted traffic.

Now we have an updated traffic requirement T' due to a single link failure, and we have to handle this traffic. The function *createTolpology* is then called again with the modified physical and logical topologies, and updated traffic requirements T'. If all the disrupted traffic can be handled successfully, we process the next failure scenario. Otherwise, the algorithm fails.

In step 9 of Figure 3.5, the function *updateTolpolgy* used to update the current topology by adding the set of newly created set of lightpaths (*new-lps*) to the previous topology LT_0. This function is also responsible for resetting traffic on all the lightpaths in the initial topology (created in step 1) to their original values. The traffic on the newly generated lightpaths (*new-lps*) is set to 0, since these lightpaths do no carry any traffic under normal fault-free conditions. This updated topology then becomes the initial topology for the following iteration, where the next faulty edge is considered. After the last fault has been handled successfully, the updated topology created in step 9 is the final survivable topology designed using our approach.

3.4.1 Example

Suppose, we are given the physical topology of Figure 3.6 and the traffic matrix specified in Table 3.1. The objective is to design a logical topology that can handle all the traffic requirements and withstand any single link failure in such a way that the number of lightpaths need to implement the topology is minimized. Since there are 7 non-zero entries in the traffic matrix, we need to consider 7 commodities in our example.

0	50	40	35
0	0	31	0
0	0	0	0
30	9	8	0

Table 3.1: Traffic Matrix.

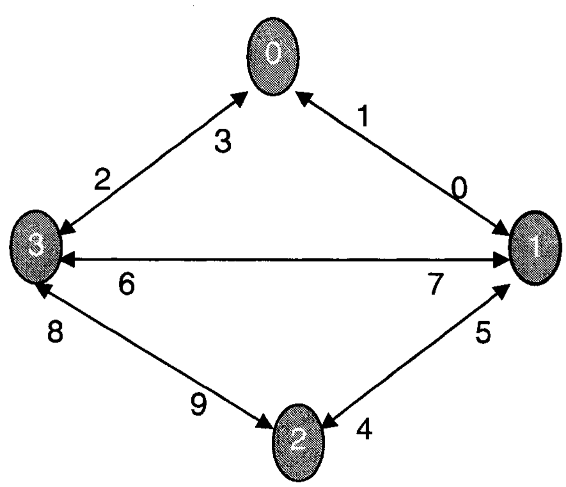


Figure 3.6: Physical topology.

After completing step 1 of our heuristic (Figure 3.5), we get the initial logical topology (LT_0) as shown in the figure 3.7. The initial topology includes 5 lightpaths L_0, L_1, L_2, L_3, and L_4 (shown using dashed lines) established over the physical topology.

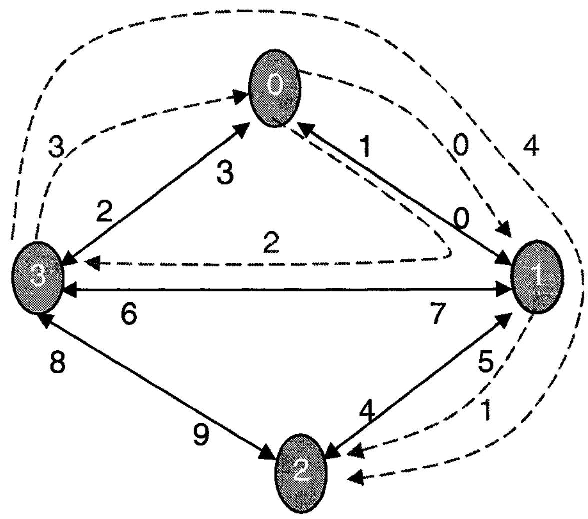


Figure 3.7: Logical topology before fault.

Table 3.2 shows the detailed information for each lightpath, including the chains which the lightpath and the total traffic on the lightpath. In this table, C_q denotes the chain corresponding to commodity q. Table 3.3 shows the details for each commodity, including the logical edges (lightpaths) in the corresponding chain.

Lightpath	Included in chains	Total traffic on lightpath
L_0: 0 → 1	C_0, C_1, C_5	99
L_1: 0 → 2	C_1	71
L_2: 0 → 3	C_2	35
L_3: 3 → 0	C_4, C_5	39
L_4: 3 → 2	C_6	8

Table 3.2: Information for each lightpath.

Commodity #	Source (s_q)	Desitnation (d_q)	Traffic (t_q)	Chain (C_q)
0	0	1	50	L_0
1	0	2	40	L_0, L_1
2	0	3	35	L_2
3	1	2	31	L_1
4	3	0	30	L_3
5	3	1	9	L_3, L_0
6	3	2	8	L_4

Table 3.3: Information for each commodity

In steps 2-9 of our algorithm (Figure 3.5), we have to consider all 10 single link failure scenarios. Here, we will investigate one physical link failure scenario in detail. The same process will have to be repeated for all physical links. Suppose, fiber link 3 ($3 \rightarrow 0$) fails. In step 4, we find the set of lightpaths using link 3. From figure 3.7, we see that lightpaths L_3 and L_4 are affected by the failure of link 3. Now in step 7(a) of the algorithm, we find out chains that contain that affected lightpaths L_3 and L_4. From Table 3.3 find that chains C_4 and C_5 use L3 and chain C6 uses L4. Now, for each disrupted chain, we need to adjust the traffic on the surviving logical edges.

- C_4 includes only a single lightpath (L3). Since it is a disrupted lightpath, we reduce the capacity of L3 to 0. We also update the traffic matrix entry (t4) for commodity 4.
- C_5 includes lightpaths L3 and L0. Capacity of the disrupted lightpath (L3) is set to 0, and the capacity of the remaining lightpath (L0) is increased by 9 units, which was the traffic carried by chain C5. We also update the traffic matrix entry (t5) for commodity 4.

- C_6 includes only a single lightpath (L4). Since it is a disrupted lightpath, we reduce the capacity of L4 to 0. We also update the traffic matrix entry (t6) for commodity 4.

The updated traffic matrix (step 6), is shown in Table 3.8

0	0	0	0
0	0	0	0
0	0	0	0
30	9	8	0

Table 3.4: Traffic matrix after fault in link 3.

Now, to handle this traffic matrix we call the *CreateTopology* function again (step 8). This function returns the set of additional lightpaths to be added to the initial topology. The new topology, after adding the new lightpaths (L_5, L_6, and L_7) is shown in figure 3.9. The whole process is repeated for each single physical link failure to obtain the final topology.

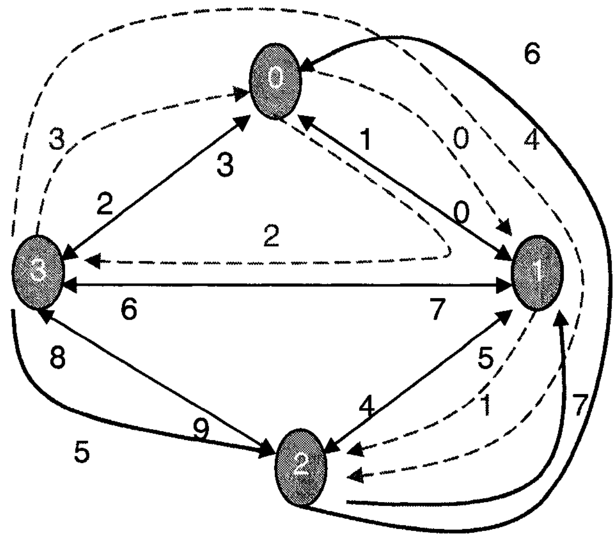


Figure 3.8: Topology after fault.

Chapter Four

4.0 Experiments and Results

In this chapter, we present the results of the experiments to study the performance of our approach, compared to existing methods for designing survivable topologies. In particular, we compare the topologies designed using our technique to those based on shared protection (SP) and dedicated protection (DP). The experiments have been carried out on a number of networks of different sizes, ranging from 6 nodes to 50 nodes. For a given network size (N nodes), 10 distinct physical topologies were randomly generated, and each topology was tested with 15 different traffic matrices T1, T2, … T15. The traffic matrices were further classified into three categories: high traffic, medium traffic and low traffic as defined below.

- Low traffic: traffic is uniformly distributed between 0 – 30 units.
- Medium traffic: traffic is uniformly distributed between 0 – 50 units
- High traffic: traffic is uniformly distributed between 0 – 80 units

For each traffic load condition we have five different traffic matrices, for a total of 15. The same data set was used to design logical topologies, using shared protection, dedicated protection and our approach. For a given physical network and traffic matrix, we have used three different values for K (K = 8, 16, and 32), where K is the number of available channels per fiber.

The topologies generated by all three approaches are capable of surviving single link failures. Therefore, in order to evaluate our technique, we compare the resources required to implement such topologies. When considering resource requirements, we are primarily interested in:

- The average number of wavelength channels used per fiber
- The average number of lightpaths created.

For a given network size and traffic load, we also want to check how many design problems are successfully handled. We consider a design to be *successful* if all the traffic requirements can be met by the topology created. Therefore, we have also studied

1. The number failures, for a given network size and maximum number of channels per fiber *K*.

4.1 Results of experiments on channel requirements

Table 4.1 presents the results of our experiments for the average number of channels required per fiber, to implement a successful topology, using our heuristic (H1), shared protection (SP) and dedicated protection (DP). The entries represent the average values for all *successful* experiments, where a viable topology could be created. If for a given value of N, and *K*, and a specified traffic condition (i.e. high, medium or low) *all* the experiments failed then we have put a '–' for the corresponding entry. For example, for N=14, and *K*=8, there were no successful designs for "high" traffic loads. Therefore, these entries are shown as -. The actual traffic matrices used in the experiments are given in Appendix B.

N	*K*	Average number of channels used per fiber								
		High Traffic			Medium Traffic			Low Traffic		
		H1	SP	DP	H1	SP	DP	H1	SP	DP
6	8	2.72	2.72	5.5	2.28	2.5	3.11	1.89	2	2.17
	16	2.72	2.72	5.5	2.28	2.5	3.11	1.89	2	2.17
	32	2.72	2.72	5.50	2.27	2.5	3.11	1.89	2	2.17
8	8	4.38	4.38	8.63	3.29	3.75	4.96	2.67	3.04	3.42
	16	4.5	4.58	8.88	3.29	3.79	4.96	2.67	3.04	3.41
	32	4.50	4.58	8.88	3.29	3.79	4.96	2.67	3.04	3.41
10	8	4.27	4.27	7.97	3.27	3.84	4.57	2.11	2.68	3.41
	16	4.38	4.57	9.03	3.27	3.84	5.14	2.11	2.68	3.38
	32	4.38	4.57	9.03	3.27	3.83	5.14	2.11	2.68	3.37
14	8	-	-	-	6.26	-	-	5.38	-	-
	16	10.36	10.83	-	7.29	8.67	11.55	5.69	7.45	8.14
	32	10.60	11.29	21.02	7.28	8.76	12.09	5.69	7.47	8.17
20	8	-	-	-	6.67	-	-	5.35	6.52	-
	16	9.96	10.76	-	7.47	8.82	12.24	5.48	7.26	7.89
	32	10.05	10.91	21.68	7.47	8.79	12.39	5.49	7.24	7.88
25	8	-	-	-	-	-	-	6.44	-	-
	16	12.22	13.03	-	9.68	11.34	-	6.98	9.07	10.3
	32	13.01	13.94	28.16	9.68	11.6	17.02	6.98	9.07	10.47
30	8	-	-	-	7.4	-	-	6.02	-	-
	16	11.26	12.26	-	8.57	10.29	-	6.26	8.16	-
	32	11.47	12.49	26.19	8.56	10.36	15.38	6.26	8.17	9.2
40	32				9.39	11.28	17.18	5.99	8.98	13.44

Table 4.1: Comparison of the average number of channels per fiber required.

4.1.1 Performance Analysis for Channels Used

Figures 4.1 and Figure 4.2 show how the average number of channels varies with size of the network, for each of the approaches. In these figures, we have used a specific value of *K* (*K*=32 and *K=16*), the results for the other cases follow a similar pattern. Figures 4.1 depict the results corresponding to low traffic loads respectively for *K=32* and Figures 4.2 depict the results corresponding to low traffic loads respectively for *K=16.* From the charts it is evident that both shared protection and our heuristic clearly outperform dedicated protection, in all cases. Our approach also performs as well as or better than shared protection in all cases. The improvement in performance is less for high traffic conditions 8% (approximately) and increases considerably to 23% (approximately) for low traffic loads. The charts resulting from the experiments are given in Appendix E.

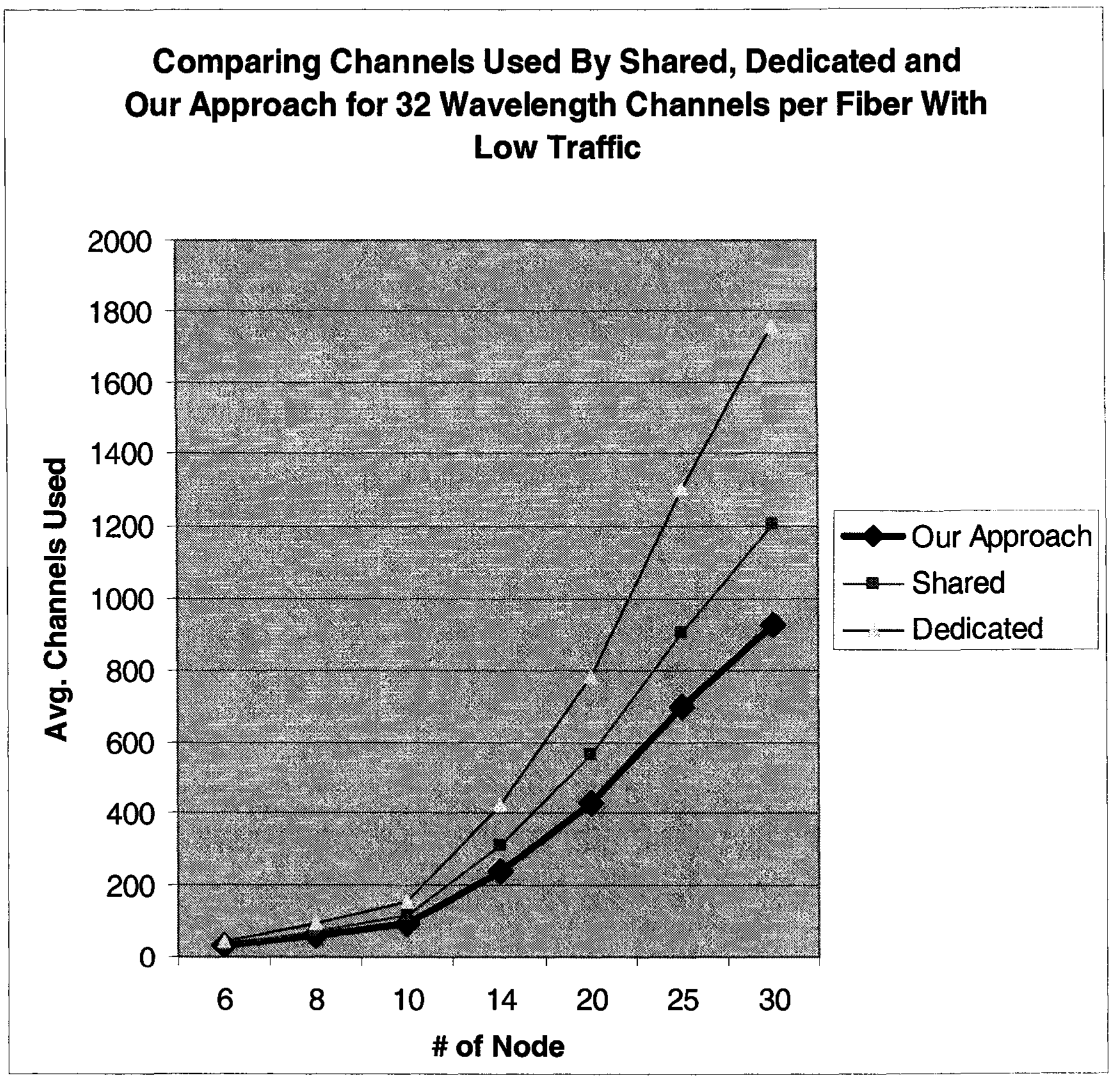


Figure 4.1: Avg. channels used by three approaches for low traffic and 32 wavelength channels.

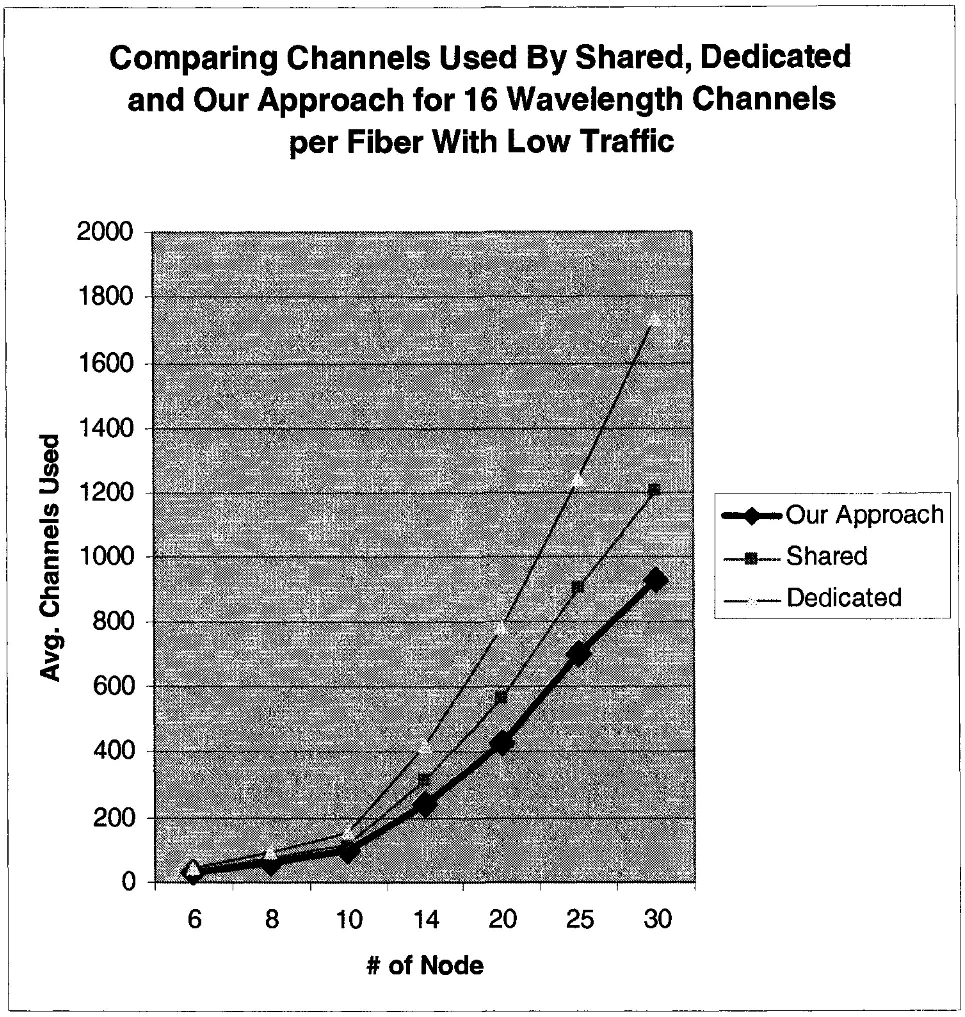


Figure 4.2: Avg. channels used by three approaches for low traffic and 16 wavelength channels.

4.2 Results of experiments on number of lightpaths

In addition to the number of channels required, another important metric is the number of lightpaths needed to implement a logical topology. Each lightpath requires one transmitter and one receiver. Therefore, it is important to try to minimize the number of lightpaths, so that the cost of transmitters and receivers can be reduced. Table 4.2 compares the average number of lightpaths required to generate feasible topologies for networks of different sizes and with different traffic loads. As before, when calculating averages, we only consider the experiments where a topology could be successfully designed to handle the required traffic.

N	*K*	Average number of lightpaths created								
		High Traffic			Medium Traffic			Low Traffic		
		H1	SP	DP	H1	SP	DP	H1	SP	DP
6	8	29	35	35	25	31	31	20	25	25
	16	29	35	35	25	31	31	20	25	25
	32	29	35	35	25	31	31	20	25	25
8	8	53	66	66	41	54	54	33	42	42
	16	53	66	66	41	54	54	33	42	42
	32	53	66	66	41	54	54	33	42	42
10	8	79	104	104	62	85	85	50	70	69
	16	79	104	104	62	86	86	50	70	70
	32	79	104	104	62	86	86	50	70	70
14	8	-	-	-	118	-	-	95	-	-
	16	166	219	-	120	168	169	96	414	140
	32	166	220	220	120	168	168	96	141	141
20	8	-	-	-	244	-	-	185	291	-
	16	323	461	-	247	364	370	186	293	292
	32	323	460	460	247	362	362	186	293	293
25	8	-	-	-	-	-	-	284	-	-
	16	502	731	-	390	601	-	287	460	462
	32	505	735	734	390	601	601	287	461	461
30	8	-	-	-	551	-	-	406	-	-
	16	716	1095	-	552	880	-	411	681	681
	32	719	1083	1082	552	883	883	411	682	682
40	32				986	1626	1626	742	1270	1270

Table 4.2: Comparison of the average number of lightpaths required.

4.2.1 Performance Analysis for Lightpaths Used

Figures 4.3 to Figure 4.8 represent the average number lightpaths required in the successful experiments, under different load conditions and for different networks with *K*=32 and *K=16.* Figures 4.3 to Figure 4.8 show that the number of lightpaths required in our approach is consistently less than the number of lightpaths required by shared and dedicated scheme. We can also see that with the increase of the size of the network, the improvement becomes more significant.

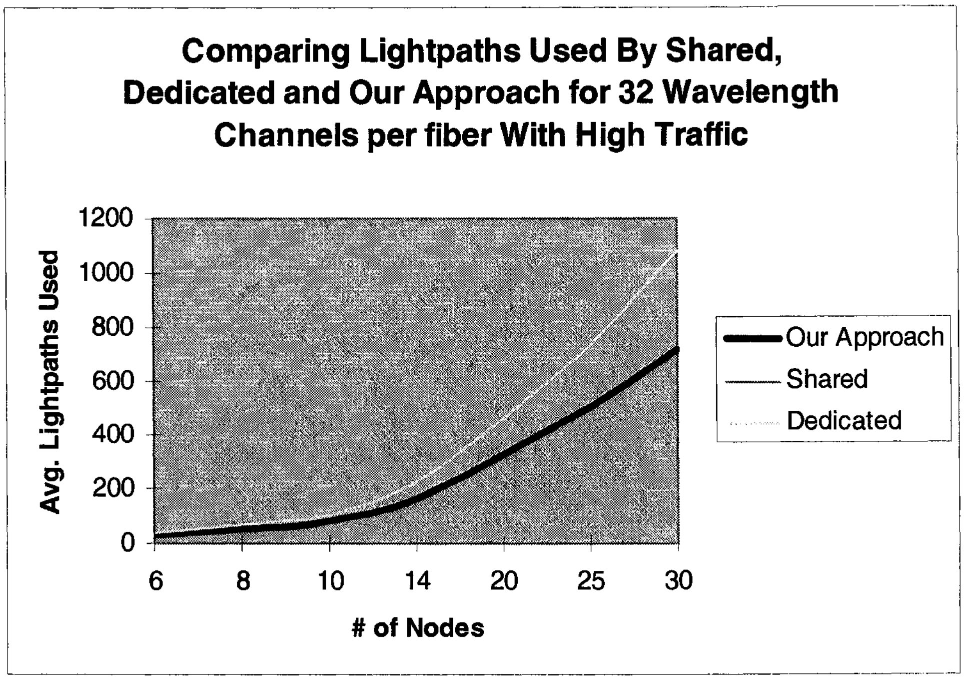


Figure 4.3: Avg. lightpaths used by three approaches for high traffic and 32 available wavelength channels.

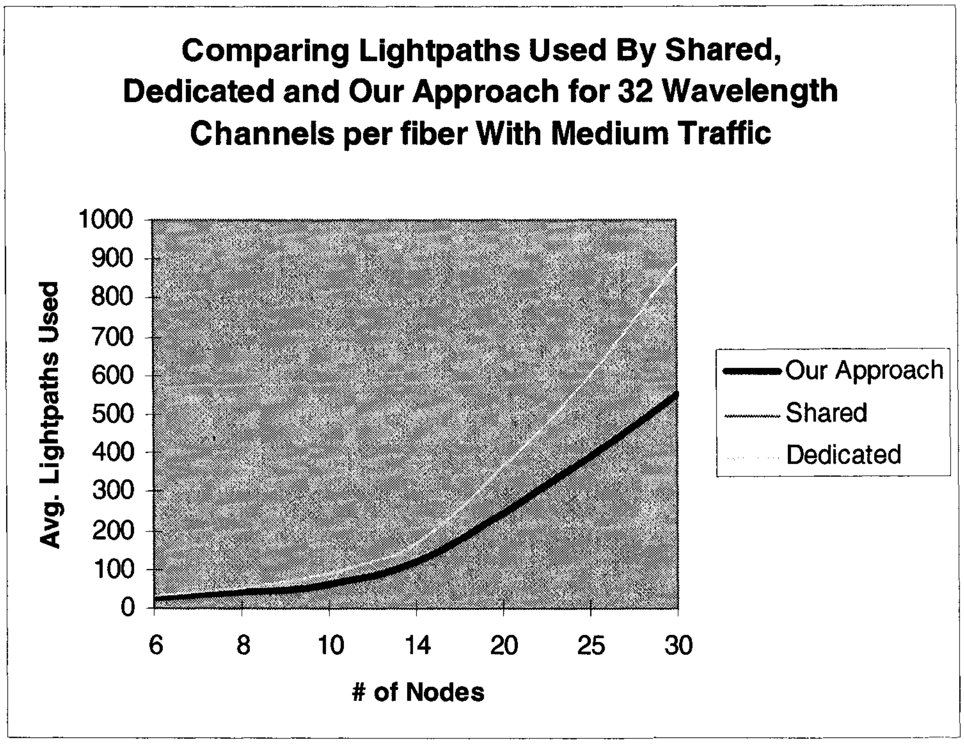


Figure 4.4: Avg. lightpaths used by three approaches for medium traffic and 32 available wavelength channels.

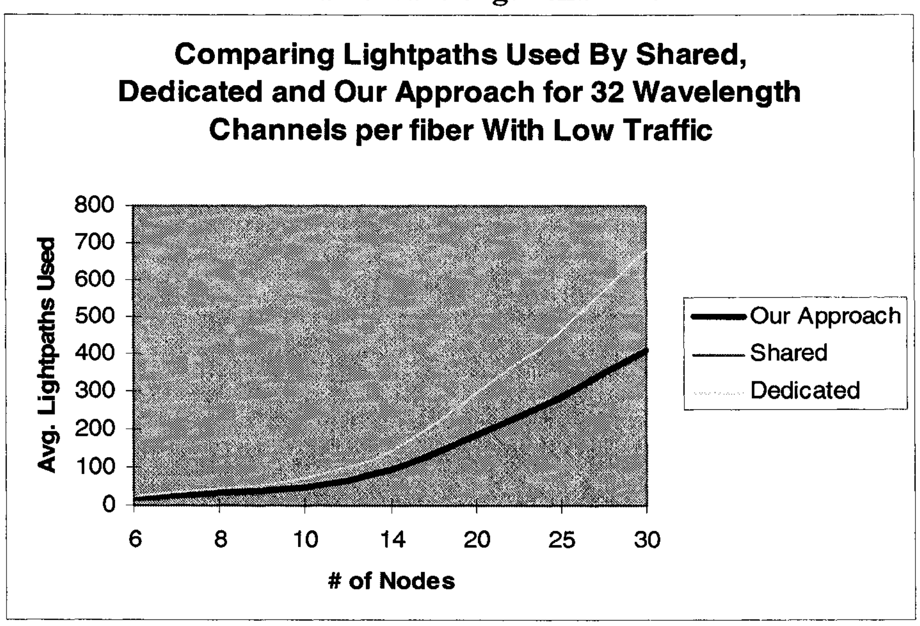


Figure 4.5: Avg. lightpaths used by three approaches for low traffic and 32 available wavelength channels.

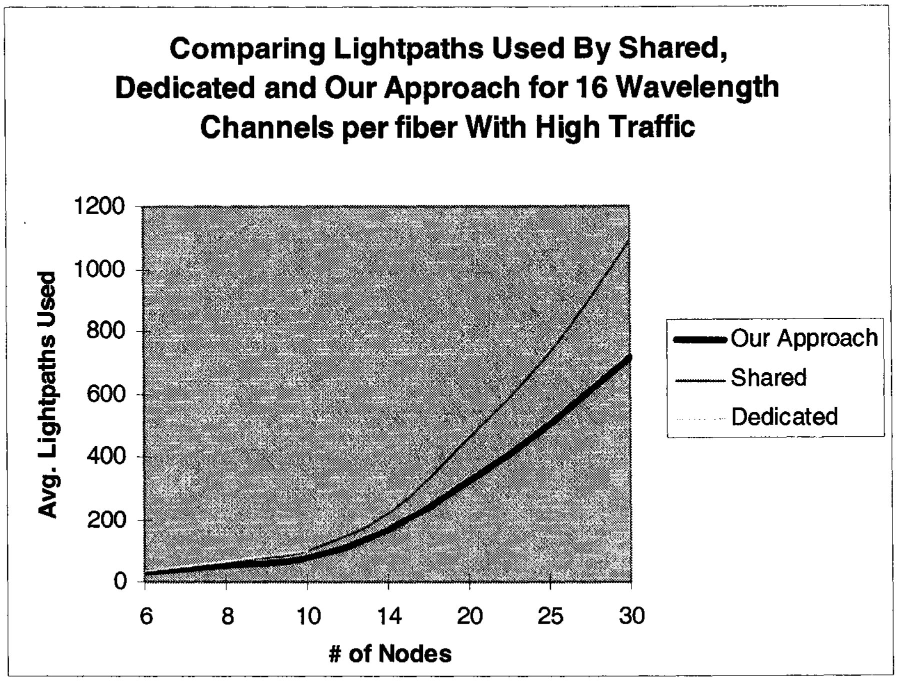


Figure 4.6: Avg. lightpaths used by three approaches for high traffic and 16 available wavelength channels.

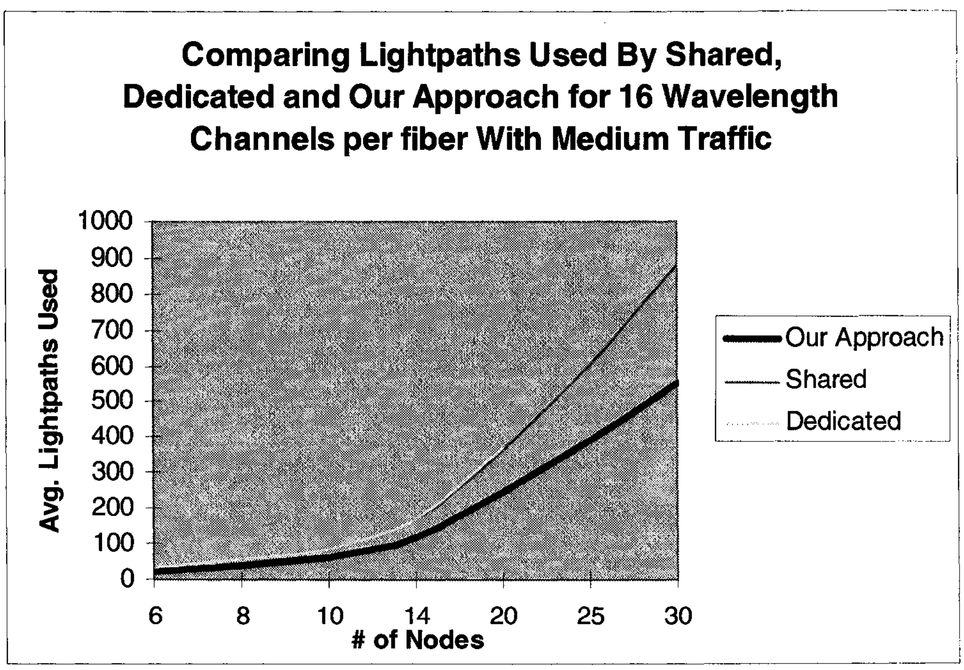


Figure 4.7: Avg. lightpaths used by three approaches for medium traffic and 16 available wavelength channels.

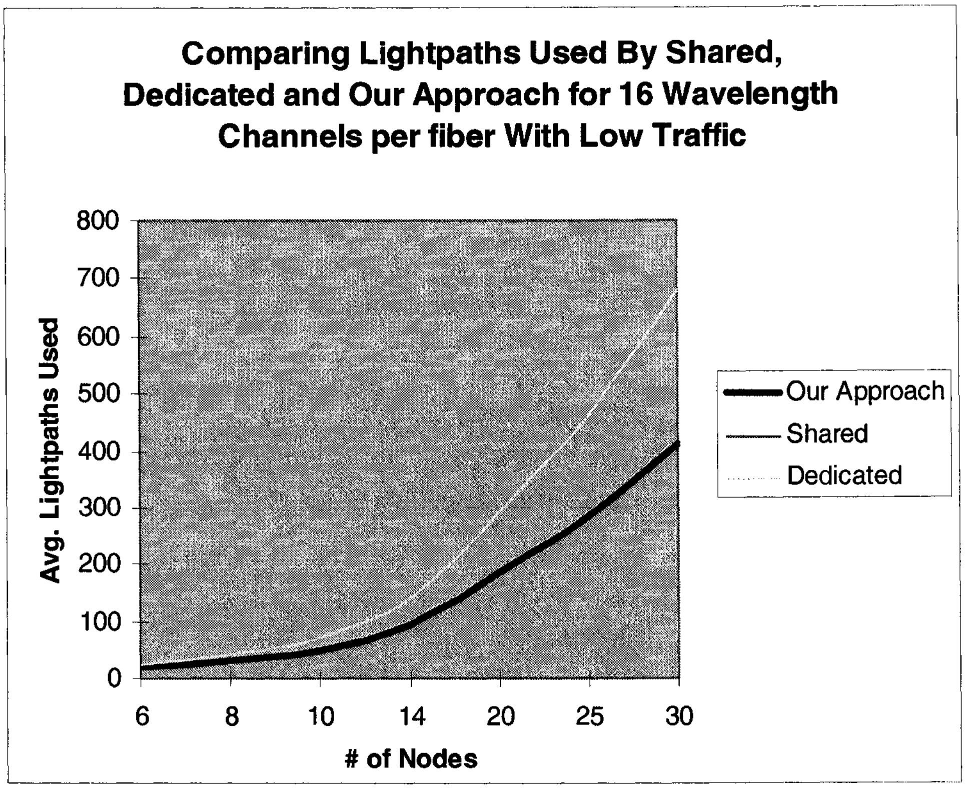


Figure 4.8: Avg. lightpaths used by three approaches for low traffic and 16 available wavelength channels.

4.3 Performance Improvement in Our Approach

In this section, we summarize the percentage improvement of our approach versus shared protection (H1vSP) and dedicated protection (H1vDP), in terms of both the number of channels used and the number of lightpaths created. Equation (4.1) is used to calculate the percentage improvement, and these values are presented in Table 4.3

$$\text{Percentage improvement} = \left(\frac{x-y}{x}\right) * 100 \quad \ldots\ldots\ldots\ldots \quad (4.1)$$

Here, x = ave. no. of channels per fiber in shared (dedicated) protection for H1vSP (H1vDP); and

y = average number of channels used in our approach

We have also compared the two existing methods to each other (SPvDP). Percentage improvement is again calculated using equation (4.1), but in this case

x = ave. no. of channels used in dedicated protection; and

y = average number of channels used in shared protection.

The values used in the above calculations are obtained from Table 4.1. If there is no valid entry for x in the table, then the corresponding entry in Table 4.3 is also '-'.

N	*K*	Percentage improvement in number of channels used per fiber								
		High Traffic			Medium Traffic			Low Traffic		
		H1vDP	H1vSP	SPvDP	H1vDP	H1vSP	SPvDP	H1vDP	H1vSP	SPvDP
6	8	50.50	0.0	50.50	26.78	8.88	19.64	24.44	5.55	20.0
	16	50.50	0.0	50.50	26.78	8.88	19.64	24.44	5.55	20.0
	32	50.50	0.0	50.50	26.78	8.88	19.64	24.44	5.55	20.0
8	8	49.27	0.0	49.27	33.61	12.22	24.36	31.18	12.32	21.50
	16	49.29	1.81	48.35	33.61	13.18	23.52	31.91	12.32	22.34
	32	49.29	1.81	48.35	33.61	13.18	23.52	31.91	12.32	22.34
10	8	46.44	0.0	46.44	28.40	14.78	15.97	36.42	17.94	22.51
	16	51.49	4.14	49.40	36.31	14.78	25.26	37.66	17.94	24.02
	32	51.49	4.14	49.40	36.31	14.78	25.26	37.66	17.94	24.02
14	8	-	-	-	-	-	-	-	-	-
	16	-	4.39	-	36.90	15.93	24.94	42.95	23.64	25.29
	32	49.60	6.11	46.31	39.76	16.84	27.55	44.02	23.88	26.46
20	8	-	-	-	-	-	-	-	18.07	-
	16	-	7.38	-	38.95	15.26	27.95	45.19	24.38	27.52
	32	53.58	7.87	49.61	39.71	15.01	29.05	45.19	24.24	27.65
25	8	-	-	-	-	-	-	-	-	-
	16	-	6.21	-	I-	14.63	-	43.80	23.04	26.97
	32	53.79	6.67	50.49	43.12	16.55	31.84	46.43	23.04	30.39
30	8	-	-	-	-	-	-	-	-	-
	16	-	8.15	-	-	16.74	-	46.56	23.34	30.29
	32	56.19	8.16	52.29	44.33	17.40	32.60	47.17	23.40	31.03
40	32				16.66	45.11	34.14	33.4	55.49	33.17

Table 4.3: Percentage improvement in number of channels per fiber.

Tables 4.4 shows the percentage improvement in the number of lightpaths created, using our approach over shared and dedicated protection. The values are calculated in exactly the same manner as for Table 4.3. The only difference is that here x and y represent the average number of lightpaths in the successful topologies, for the different approaches.

N	*K*	Percentage improvement in average number of lightpaths								
		High Traffic			Medium Traffic			Low Traffic		
		H1vDP	H1vSP	SPvDP	H1vDP	H1vSP	SPvDP	H1vDP	H1vSP	SPvDP
6	8	17.14	17.14	0.0	19.35	19.35	0.0	20.0	20.0	0.0
	16	17.14	17.14	0.0	19.35	19.35	0.0	20.0	20.0	0.0
	32	17.14	17.14	0.0	19.35	19.35	0.0	20.0	20.0	0.0
8	8	19.69	19.69	0.0	24.07	24.07	0.0	21.42	21.42	0.0
	16	19.69	19.69	0.0	24.07	24.07	0.0	21.42	21.42	0.0
	32	19.69	19.69	0.0	24.07	24.07	0.0	21.42	21.42	0.0
10	8	23.30	24.03	-	27.05	27.05	0.0	27.53	28.57	-
	16	24.03	24.02	0.0	27.90	27.90	0.0	28.57	28.57	0.0
	32	24.03	24.03	0.0	27.90	27.90	0.0	28.57	28.57	0.0
14	8	-	-	-	-	-	-	-	-	-
	16	-	24.20	-	28.99	28.57	0.59	31.42	31.91	-
	32	24.54	24.54	0.0	28.57	28.57	0.0	31.91	31.91	0.0
20	8	-	-	-	-	-	-	-	36.42	-
	16	-	29.93	-	33.24	32.14	1.62	36.30	36.51	-
	32	29.78	29.78	0.0	31.76	31.76	0.0	36.51	36.51	0.0
25	8	-	-	-	-	-	-	-	-	-
	16	-	31.32	-	-	35.10	-	37.87	37.60	0.43
	32	31.19	31.29	-	35.10	35.10	0.0	37.74	37.74	0.0
30	8	-	-	-	-	-	-	-	-	-
	16	-	34.61	-	-	37.27	-	39.64	39.64	0.0
	32	33.54	33.61	-	37.48	37.48	0.0	39.73	39.73	0.0
40	32				39.36	39.36	0.0	41.57	41.57	0.0

Table 4.4: Percentage improvement in average number of lightpaths.

4.4 Failure analysis

Table 4.5 depicts the failure rates for topology design, under different traffic load conditions and different number of available channels per fiber (*K*). We consider a design to be successful, if *all* the traffic requirements can be handled by the generated logical topology; otherwise it is counted as "failure". From Table 4.5 we see that, as expected, the failure rate decreases as the available resources (i.e. number of available channels per fiber) are increased. Also it is clear that the failure rate for our approach is *always* less than the other to approaches. This indicates that our heuristic makes more efficient use of available resources.

N	*K*	Number of failures								
		High Traffic			Medium Traffic			Low Traffic		
		H1	SP	DP	H1	SP	DP	H1	SP	DP
6	8	0	0	0	0	0	0	0	0	0
	16	0	0	0	0	0	0	0	0	0
	32	0	0	0	0	0	0	0	0	0
8	8	2	6	23	0	0	2	0	0	0
	16	0	0	0	0	0	0	0	0	0
	32	0	0	0	0	0	0	0	0	0
10	8	0	16	32	0	0	24	0	0	6
	16	0	0	0	0	0	0	0	0	0
	32	0	0	0	0	0	0	0	0	0
14	8	50	50	50	30	50	50	4	50	50
	16	3	12	50	0	1	28	0	0	3
	32	0	0	0	0	0	0	0	0	0
20	8	50	50	50	32	50	50	0	48	50
	16	0	6	50	0	0	32	0	0	0
	32	0	0	0	0	0	0	0	0	0
25	8	50	50	50	50	50	50	17	50	50
	16	3	48	50	0	8	50	0	0	46
	32	0	0	1	0	0	0	0	0	0
30	8	50	50	50	49	50	50	2	50	50
	16	0	23	50	0	2	50	0	0	7
	32	0	0	0	0	0	0	0	0	0
40	32				0	0	0	0	0	0

Table 4.5: Comparison of the number of failures in each approach.

4.5 Statistical analysis of our results.

In this section, we analyze the statistical significance of our results. For each set of experiments, we calculate the 95% confidence interval (C.I). This interval is specified by an upper bound (U) and a lower bound (L), and signifies that we are 95% confident that the mean of the samples will be with in the cosnfidence limits L and U. The confidence interval is calculated using equations (4.3) and (4.4).

$$95\%\ \text{C.I.} = \bar{x} \pm 1.96 \times \frac{s}{\sqrt{n}} \quad \ldots\ldots (4.3)$$

Where, $\bar{x}$ = mean of the samples,

n = size of the samples, and

s = standard deviation, calculated using the equation 4.4

$$s^2 = \frac{\sum(x-\bar{x})^2}{(n-1)} \quad \ldots\ldots (4.4)$$

For example, in Table 4.6, for a 20 node network, with K=32, and low traffic conditions, the 95% C.I. is between 23.38 and 25.11, for H1vSP. This means that, we are 95% confident that the mean of percentage improvement (in terms of number of channels used) of our approach vs. shared protection will not be less than 23.38 and will not be more than 25.11. Confidence intervals for the different experiments are presented in Appendix F.

4.5.1 95% Confidence Interval for Channels Used

High	Wave length Channels	Our vs. Shared Protection		Dedicated vs. Our Approach		Dedicated vs. Shared Protection	
Node Number		95% Confidence Interval		95% Confidence Interval		95% Confidence Interval	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound
6	8	2.99	10.27	20.89	27.38	17.74	19.91
	16	2.99	10.27	20.89	27.38	17.74	19.91
	32	2.99	10.27	20.89	27.38	17.74	19.91
8	8	9.61	13.53	29.59	32.91	21.03	23.34
	16	9.61	13.53	29.61	33.02	21.18	23.40
	32	9.61	13.53	29.61	33.02	21.18	23.40
10	8	15.94	19.38	35.95	38.59	23.02	24.53
	16	15.94	19.38	36.30	38.71	23.23	24.81
	32	15.94	19.38	36.30	38.71	23.23	24.81
14	8	10.12	12.83	12.71	15.45	1.69	4.05
	16	22.21	24.57	41.98	43.77	24.52	26.24
	32	22.45	24.89	42.79	44.74	25.34	27.20
20	8	15.88	17.59	18.90	20.55	2.79	4.33
	16	23.36	25.11	44.68	45.67	26.87	28.27
	32	23.38	25.11	44.68	45.76	27.19	28.11
25	8	1.31	2.83	1.94	3.83	0.17	1.48
	16	22.50	23.44	43.75	44.77	27.03	28.23
	32	22.64	23.54	46.15	46.70	30.03	30.65
30	8	10.01	11.84	10.60	12.30	0.09	1.05
	16	22.90	23.72	46.57	47.13	30.33	31.04
	32	22.97	23.79	46.92	47.41	30.80	31.29

Table 4.6: 95% C.I. for channels used under low traffic condition.

4.5.2 95% Confidence Interval for Lightpath Used

Table 4.7 represents the C.I. for lightpaths used under different traffic load conditions and different available wavelength channels. In Table 4.8, for 32 available wavelength channels, 20 node networks and our vs. shared approach, 95% C.I. is 31.33 and 32.05. In other words, we are 95% confident that the mean of percentage improvement of lightpaths used in our approach vs. shared protection will not be less than 31.33 and will not be more than 32.05. Confidence intervals for the different experiments are presented in Appendix G.

High	Wave length Channels	Our vs. Shared Protection		Dedicated vs. Our Approach	
Node Number		95% Confidence Interval		95% Confidence Interval	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
6	8	17.40	19.99	17.40	19.99
	16	17.40	19.99	17.40	19.9
	32	17.40	19.99	17.40	19.99
8	8	21.95	24.75	22.30	25.03
	16	21.86	24.47	21.86	24.47
	32	21.86	24.47	21.86	24.47
10	8	26.58	28.70	22.80	26.32
	16	26.51	28.65	26.51	28.65
	32	26.51	28.65	26.51	28.65
14	8	10.04	13.87	-	-
	16	27.60	28.69	27.03	28.20
	32	27.49	28.46	27.53	28.58
20	8	17.44	19.88	-	-
	16	31.53	32.41	33.47	34.54
	32	31.33	32.05	31.33	32.05
25	8	-	-	-	-
	16	34.91	35.59	22.21	24.31
	32	34.72	35.30	34.73	35.31
30	8	9.37	11.17	-	-
	16	37.10	37.53	33.44	34.56
	32	37.28	37.65	37.28	37.65

Table 4.7: 95% C.I. for lightpaths used under medium traffic condition.

Chapter Five

5.0. Conclusions and Future Work

The objective of this thesis was to develop an efficient technique for designing fault tolerant logical topologies for WDM networks. This final logical topology should be able to withstand any single link failure in the network. The inputs to the design process were underlying physical topology, the amount and distribution of traffic to be handled by the network and resource constraints on the number of optical components at each node. A MILP formulation for this problem can be used to generate optimal solutions. But, the problem becomes computationally intractable, even for relatively small networks. Therefore, efficient heuristics are required to solve this problem.

In this thesis, we have presented a quick and efficient heuristic for fault tolerant logical topology design. One of the main objectives of our design process is to keep the cost of the network as low as possible. In current WDM networks, it is possible to support hundreds of WDM channels on a single fiber. Therefore, the cost of transmitters and receivers is becoming the main factors determining the cost of the network. This cost can be minimized by keeping the number of lightpaths as low as possible. Therefore, we have tried to minimize the cost of the network by reducing the number of lightpaths required to implement a topology. When we process a specific traffic request, we try to use existing lightpaths as much as possible. If we have to create new lightpaths, we try to minimize the number of new lightpaths.

We have tested our heuristics on a number networks, ranging in size from 6 nodes to 50 nodes. For a given network size, we have experiments with over 100 data sets. We have compared our results with two widely used approaches for survivable network design - shared protection and dedicated protection techniques. The results clearly show that our heuristic provides a significant improvement over the existing techniques, both in terms of the number of WDM channels used and the number of lightpaths required to implement a topology.

The results also indicate that, in many cases, we are able to design a feasible topology, when both shared and dedicated protection schemes fail, with the same amount of available resources.

Future Work

In our heuristic, for any specific traffic request, route the entire traffic request along a single chain. If we allow the traffic to be split and distributed over several routes, it may be possible to accommodate the traffic without creating new lightpaths, even if a single chain capable of carrying the entire traffic cannot be found. Our algorithm can be augmented to all multiple chains for a single commodity.

Our heuristic specifies a routing strategy to route the traffic over the generated logical topology. Although this routing is feasible, it is not guaranteed to be optimal. Our heuristic can be enhanced, by adding another step which takes the logical topology and traffic matrix, and optimally routes the traffic over the topology. This is a significant work in itself and is being carried out by another graduate student.

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Appendix A: Abbreviations

1. WDM - Wavelength Division Multiplexing
2. ILP - Integer Linear Programming
3. LP - Linear Programming
4. MILP - Mixed-Integer Linear Programming
5. OXC - Optical Cross-Connect
6. RWA - Routing & Wavelength Assignment
7. WAN - Wide Area Network
8. LAN - Local Area NetworkS

Appendix B: Traffic Matrix

In Our Experiments, we have used 15 traffic matrices in which 5 for high traffic, 5 for medium traffic and 5 for low traffic. Now, we will list one traffic matrix from each category for each N-node Networks.

Traffic Matrix for 6 Node Network

- High Traffic

0	0	13	63	22	9
20	0	68	72	56	56
39	31	0	31	43	65
28	73	10	0	6	9
12	37	7	52	0	68
20	63	69	72	4	0

- Medium Traffic

0	0	33	43	12	29
0	0	8	2	6	6
19	11	0	1	43	5
8	43	30	0	16	19
32	17	47	22	0	18
30	23	49	42	14	0

- Low

0	0	23	3	2	29
0	0	18	22	6	26
19	21	0	11	3	5
18	23	0	0	6	29
2	7	17	2	0	8
10	13	9	12	24	0

Traffic Matrix for 8 Node Network

- High Traffic

0	0	13	63	22	9	20	68
72	0	56	56	39	31	31	43
65	28	0	73	10	6	9	12

37	7	52	0	68	20	63	69
72	4	9	71	0	27	30	64
75	40	24	30	22	0	4	3
21	70	36	36	31	9	0	77
35	11	30	64	54	25	29	0

- Medium Traffic

0	0	33	43	12	29	0	8
2	0	6	6	19	11	1	43
5	8	0	43	30	16	19	32
17	47	22	0	18	30	23	49
42	14	19	1	0	27	40	24
35	20	44	10	12	0	34	13
1	10	36	26	31	29	0	47
25	41	40	44	34	25	29	0

- Low Traffic

0	0	23	3	2	29	0	18
22	0	6	26	19	21	11	3
5	18	0	23	0	6	29	2
7	17	2	0	8	10	13	9
12	24	19	21	0	17	10	24
15	20	14	20	22	0	14	3
21	0	6	16	21	9	0	7
25	21	20	24	24	25	9	0

Traffic Matrix for 10 Node Network

- High Traffic

0	0	13	63	22	9	20	68	72	56
56	0	39	31	31	43	65	28	73	10
6	9	0	12	37	7	52	68	20	63
69	72	4	0	9	71	27	30	64	75
40	24	30	22	0	4	3	21	70	36
36	31	9	77	35	0	11	30	64	54
25	29	30	7	6	63	0	54	24	40
69	20	16	52	52	13	10	0	29	79
45	15	49	7	79	57	24	36	0	9
76	24	53	5	47	26	29	34	32	0

- Medium Traffic

0	0	33	43	12	29	0	8	2	6
6	0	19	11	1	43	5	8	43	30
16	19	0	32	17	47	22	18	30	23
49	42	14	0	19	1	27	40	24	35
20	44	10	12	0	34	13	1	10	36
26	31	29	47	25	0	41	40	44	34
25	29	30	27	26	43	0	34	4	10
49	20	6	32	22	13	40	0	9	19
5	45	49	27	19	47	24	46	0	49
6	34	43	45	7	6	9	4	2	0

- Low Traffic

0	0	13	3	2	9	0	8	12	16
16	0	19	11	11	3	5	8	13	10
6	9	0	12	17	7	12	8	0	3
9	12	4	0	9	11	7	10	4	15
0	4	10	2	0	4	3	1	10	16
16	11	9	17	15	0	11	10	4	14
5	9	10	7	6	3	0	14	4	0
9	0	16	12	12	13	10	0	9	19
5	15	9	7	19	17	4	16	0	9
16	4	13	5	7	6	9	14	12	0

Traffic Matrix for 14 Node Network

- High Traffic

0	0	13	63	22	9	20	68	72	56	56	39	31	31
43	0	65	28	73	10	6	9	12	37	7	52	68	20
63	69	0	72	4	9	71	27	30	64	75	40	24	30
22	4	3	0	21	70	36	36	31	9	77	35	11	30
64	54	25	29	0	30	7	6	63	54	24	40	69	20
16	52	52	13	10	0	29	79	45	15	49	7	79	57
24	36	9	76	24	53	0	5	47	26	29	34	32	65
63	18	1	10	50	57	35	0	16	43	11	67	42	66
8	52	41	30	0	18	11	51	0	14	47	4	77	25
38	51	18	7	71	67	73	19	35	0	70	70	33	42
14	33	27	41	30	20	37	78	6	23	0	37	8	13
68	38	45	13	68	0	11	26	67	30	9	0	47	28
63	33	60	74	65	23	72	50	27	22	50	65	0	30
40	76	62	25	20	7	4	51	38	26	19	0	55	0

- Medium Traffic

0	0	29	15	38	41	36	36	40	24	8	7	15	47
27	0	17	12	41	42	6	41	44	37	23	20	20	4

31	21	0	24	36	25	39	11	46	0	27	8	8	14
22	20	3	0	21	6	36	4	15	9	13	19	27	14
0	6	25	45	0	30	39	38	15	22	24	40	5	20
16	20	4	29	10	0	29	47	45	15	17	39	31	41
8	36	9	44	8	21	0	21	31	26	29	2	16	17
47	18	1	10	18	25	19	0	16	11	11	3	10	2
8	4	9	14	32	34	27	3	0	14	31	4	45	9
6	3	18	39	39	19	9	35	3	0	6	38	17	10
14	1	11	25	30	20	21	46	22	39	0	5	24	45
4	38	13	45	36	0	11	26	3	14	25	0	31	28
15	17	12	26	17	23	40	34	43	22	34	33	0	30
24	44	30	25	36	39	20	35	6	26	35	0	7	0

- Low Traffic

0	0	23	3	2	29	0	18	22	6	26	19	21	11
3	0	5	18	23	0	6	29	2	7	17	2	8	10
13	9	0	12	24	19	21	17	10	24	15	20	14	20
22	14	3	0	21	0	6	16	21	9	7	25	21	20
24	24	25	9	0	0	27	26	3	4	24	10	29	20
16	2	22	23	10	0	29	29	15	15	29	27	19	17
14	6	9	26	14	3	0	15	7	26	29	14	22	5
23	18	1	10	0	7	25	0	16	23	11	27	22	26
8	22	21	20	20	28	21	21	0	14	7	4	27	15
18	21	18	27	21	7	3	29	15	0	0	20	23	22
14	13	17	1	0	20	27	28	16	3	0	17	18	3
28	8	25	3	18	0	11	26	27	20	19	0	7	28
3	23	0	14	5	23	22	10	7	22	10	15	0	0
0	26	12	25	0	27	14	11	18	26	29	0	25	0

Traffic Matrix for 20 Node Network

- High Traffic

0	0	13	63	22	9	20	68	72	56	56	39	31	31	43	65	28	73	10	6
9	0	12	37	7	52	68	20	63	69	72	4	9	71	27	30	64	75	40	24
30	22	0	4	3	21	70	36	36	31	9	77	35	11	30	64	54	25	29	30
7	6	63	0	54	24	40	69	20	16	52	52	13	10	29	79	45	15	49	7
79	57	24	36	0	9	76	24	53	5	47	26	29	34	32	65	63	18	1	10
50	57	35	16	43	0	11	67	42	66	8	52	41	30	0	18	11	51	14	47
4	77	25	38	51	18	0	7	71	67	73	19	35	70	70	33	42	14	33	27
41	30	20	37	78	6	23	0	37	8	13	68	38	45	13	68	0	11	26	67
30	9	47	28	63	33	60	74	0	65	23	72	50	27	22	50	65	30	40	76

62	25	20	7	4	51	38	26	19	0	0	55	55	2	34	21	46	2	68	5
70	38	3	9	66	79	10	55	12	73	0	54	75	10	73	15	10	15	5	65
14	68	33	33	74	40	21	36	44	23	40	0	57	39	55	29	9	10	47	17
55	27	13	26	5	32	52	75	33	13	63	37	0	15	17	56	37	56	39	14
8	42	1	15	70	76	14	21	10	40	44	26	79	0	47	34	79	22	5	53
52	76	32	3	57	67	63	30	67	36	26	39	8	71	0	27	16	40	33	48
74	30	37	8	40	4	54	10	39	5	58	51	21	69	31	0	62	17	12	4
55	71	33	65	18	16	22	37	48	52	77	4	23	75	29	7	0	16	62	7
45	43	20	38	16	11	47	7	37	18	10	49	10	40	76	41	53	0	9	73
18	10	34	63	49	8	71	52	1	34	54	13	45	29	45	57	58	41	0	8
23	69	55	29	9	68	74	3	61	31	36	44	37	32	5	51	12	62	52	0

- Medium Traffic

0	0	33	43	12	29	0	8	2	6	6	19	11	1	43	5	8	43	30	16
19	0	32	17	47	22	18	30	23	49	42	14	19	1	27	40	24	35	20	44
10	12	0	34	13	1	10	36	26	31	29	47	25	41	40	44	34	25	29	30
27	26	43	0	34	4	10	49	20	6	32	22	13	40	9	19	5	45	49	27
19	47	24	46	0	49	6	34	43	45	7	6	9	4	2	15	33	38	1	40
30	37	45	6	13	0	11	27	42	6	18	12	1	10	30	8	21	31	14	47
14	47	25	38	31	18	0	37	1	37	13	29	45	0	0	13	12	34	23	47
21	30	40	7	28	26	3	0	47	8	43	38	38	35	43	38	20	11	46	37
10	9	37	18	3	23	0	24	0	5	33	2	20	37	2	10	5	10	0	46
42	35	10	47	24	31	8	36	19	0	0	15	5	32	24	11	6	2	18	15
20	18	23	39	6	19	30	5	32	43	0	24	45	10	23	5	30	45	45	5
44	48	23	3	24	10	41	6	44	43	40	0	37	29	35	49	29	10	7	17
5	37	23	26	45	12	22	45	3	3	33	17	0	5	17	26	27	26	49	4
28	2	11	5	20	16	44	31	30	30	4	36	9	0	7	4	29	2	15	3
32	36	32	13	17	7	33	10	17	16	46	19	28	21	0	7	6	20	3	28
4	30	27	48	20	4	14	10	19	25	48	31	1	9	1	0	22	17	2	24
45	21	3	25	28	16	42	47	38	32	17	4	43	45	49	7	0	36	2	17
45	13	40	48	46	1	7	17	47	28	0	9	30	10	16	11	43	0	9	3
48	30	34	43	39	38	31	42	1	24	44	43	15	49	15	37	8	41	0	48
43	29	15	39	9	38	4	43	1	21	16	14	27	12	5	11	12	32	42	0

- Low Traffic

0	0	23	3	2	29	0	18	22	6	26	19	21	11	3	5	18	23	0	6
29	0	2	7	17	2	8	10	13	9	12	24	19	21	17	10	24	15	20	14
20	22	0	14	3	21	0	6	16	21	9	7	25	21	20	24	24	25	9	0
27	26	3	0	4	24	10	29	20	16	2	22	23	10	29	29	15	15	29	27
19	17	14	6	0	9	26	14	3	15	7	26	29	14	22	5	23	18	1	10
0	7	25	16	23	0	11	27	22	26	8	22	21	20	20	28	21	21	14	7
4	27	15	18	21	18	0	27	21	7	3	29	15	0	20	23	22	14	13	17
1	0	20	27	28	16	3	0	17	18	3	28	8	25	3	18	0	11	26	27

20	19	7	28	3	23	0	14	0	5	23	22	10	7	22	10	15	0	0	26
12	25	0	27	14	11	18	26	29	0	0	25	15	22	4	1	26	22	8	25
0	8	3	29	26	29	20	25	12	23	0	24	5	10	23	25	10	25	15	15
4	18	23	3	4	20	11	16	24	3	10	0	27	29	25	19	29	20	27	27
15	7	13	6	5	12	2	15	3	13	3	27	0	5	7	6	17	26	29	14
8	2	1	15	0	6	4	11	0	0	4	6	19	0	27	4	29	22	15	13
22	16	12	3	7	27	23	0	7	26	16	19	18	11	0	7	26	10	13	28
24	0	17	18	0	4	4	20	9	15	18	21	11	19	11	0	22	17	2	24
5	1	13	5	28	6	12	17	18	22	7	24	13	5	29	27	0	26	2	7
15	23	20	28	16	21	27	27	7	18	0	19	0	10	16	21	3	0	19	23
28	20	24	23	9	8	21	12	11	24	4	13	25	29	15	17	8	11	0	8
3	29	15	9	29	8	4	3	21	21	6	24	27	12	25	1	12	2	2	0

Traffic Matrix for 25 Node Network

- High Traffic

0	0	13	63	22	9	20	68	72	56	56	39	31	31	43	65	28	73	10	6	9	12	37	7	52
68	0	20	63	69	72	4	9	71	27	30	64	75	40	24	30	22	4	3	21	70	36	36	31	9
77	35	0	11	30	64	54	25	29	30	7	6	63	54	24	40	69	20	16	52	52	13	10	29	79
45	15	49	0	7	79	57	24	36	9	76	24	53	5	47	26	29	34	32	65	63	18	1	10	50
57	35	16	43	0	11	67	42	66	8	52	41	30	0	18	11	51	14	47	4	77	25	38	51	18
7	71	67	73	19	0	35	70	70	33	42	14	33	27	41	30	20	37	78	6	23	37	8	13	68
38	45	13	68	0	11	0	26	67	30	9	47	28	63	33	60	74	65	23	72	50	27	22	50	65
30	40	76	62	25	20	7	0	4	51	38	26	19	0	55	55	2	34	21	46	2	68	5	70	38
3	9	66	79	10	55	12	73	0	54	75	10	73	15	10	15	5	65	14	68	33	33	74	40	21
36	44	23	40	57	39	55	29	9	0	10	47	17	55	27	13	26	5	32	52	75	33	13	63	37
15	17	56	37	56	39	14	8	42	1	0	15	70	76	14	21	10	40	44	26	79	47	34	79	22
5	53	52	76	32	3	57	67	63	30	67	0	36	26	39	8	71	27	16	40	33	48	74	30	37
8	40	4	54	10	39	5	58	51	21	69	31	0	62	17	12	4	55	71	33	65	18	16	22	37
48	52	77	4	23	75	29	7	16	62	7	45	43	0	20	38	16	11	47	7	37	18	10	49	10
40	76	41	53	9	73	18	10	34	63	49	8	71	52	0	1	34	54	13	45	29	45	57	58	41
8	23	69	55	29	9	68	74	3	61	31	36	44	37	32	0	5	51	12	62	52	3	1	4	4
77	42	4	3	31	33	15	66	79	66	56	59	3	38	57	4	0	67	36	28	5	14	34	79	70
3	43	64	7	42	47	76	49	32	68	24	13	38	42	14	7	48	0	26	71	40	32	78	38	38
28	55	19	39	3	36	19	76	26	0	72	30	54	35	11	71	19	76	0	20	56	23	73	15	48
1	65	29	77	57	6	17	17	42	34	26	37	49	60	1	26	52	13	20	0	10	56	12	6	34
65	7	27	75	58	63	70	62	14	44	31	72	45	0	31	19	77	41	40	31	0	15	40	6	72
68	58	66	18	26	28	14	23	23	42	31	13	48	37	31	39	72	52	72	60	63	0	38	49	12
42	48	56	32	77	63	42	64	16	70	75	65	8	44	66	5	55	44	4	73	58	24	0	61	29
17	64	66	4	51	77	38	65	19	19	15	48	57	20	38	46	77	15	34	68	2	36	39	0	62
16	61	7	51	2	74	41	62	57	73	45	78	35	58	0	37	79	8	51	47	56	28	64	10	0

- Medium Traffic

0	0	33	43	12	29	0	8	2	6	6	19	11	1	43	5	8	43	30	16	19	32	17	47	22
18	0	30	23	49	42	14	19	1	27	40	24	35	20	44	10	12	34	13	1	10	36	26	31	29
47	25	0	41	40	44	34	25	29	30	27	26	43	34	4	10	49	20	6	32	22	13	40	9	19
5	45	49	0	27	19	47	24	46	49	6	34	43	45	7	6	9	4	2	15	33	38	1	40	30
37	45	6	13	0	11	27	42	6	18	12	1	10	30	8	21	31	14	47	14	47	25	38	31	18
37	1	37	13	29	0	45	0	0	13	12	34	23	47	21	30	40	7	28	26	3	47	8	43	38
38	35	43	38	20	11	0	46	37	10	9	37	18	3	23	0	24	5	33	2	20	37	2	10	5
10	0	46	42	35	10	47	0	24	31	8	36	19	0	15	5	32	24	11	6	2	18	15	20	18
23	39	6	19	30	5	32	43	0	24	45	10	23	5	30	45	45	5	44	48	23	3	24	10	41
6	44	43	40	37	29	35	49	29	0	10	7	17	5	37	23	26	45	12	22	45	3	3	33	17
5	17	26	27	26	49	4	28	2	11	0	5	20	16	44	31	30	30	4	36	9	7	4	29	2
15	3	32	36	32	13	17	7	33	10	17	0	16	46	19	28	21	7	6	20	3	28	4	30	27
48	20	4	14	10	19	25	48	31	1	9	1	0	22	17	2	24	45	21	3	25	28	16	42	47
38	32	17	4	43	45	49	7	36	2	17	45	13	0	40	48	46	1	7	17	47	28	0	9	30
10	16	11	43	9	3	48	30	34	43	39	38	31	42	0	1	24	44	43	15	49	15	37	8	41
48	43	29	15	39	9	38	4	43	1	21	16	14	27	12	0	5	11	12	32	42	23	1	24	4
37	2	4	13	41	23	25	6	9	26	46	9	13	8	27	34	0	47	6	48	5	4	44	9	30
23	33	24	47	2	47	26	49	42	38	4	33	8	42	14	17	28	0	6	41	0	42	18	48	18
18	25	29	19	13	46	29	16	16	40	32	30	14	5	21	11	29	46	0	0	16	3	43	5	28
31	5	29	37	47	36	7	27	32	4	6	7	29	30	41	16	2	33	10	0	40	16	32	6	14
35	47	27	35	8	33	10	42	24	4	21	22	5	30	21	29	17	31	30	41	0	25	0	46	32
18	8	26	28	16	18	4	3	13	22	11	43	48	7	31	19	12	42	32	20	23	0	38	9	2
22	28	26	2	17	23	2	4	36	0	35	25	28	14	26	15	25	4	14	23	8	24	0	21	29
27	24	26	4	1	37	38	25	29	19	25	38	47	20	28	16	47	5	24	28	2	26	29	0	32
26	11	27	41	32	24	11	42	47	33	5	18	25	38	20	7	39	38	21	27	6	18	14	20	0

- Low Traffic

0	0	23	3	2	29	0	18	22	6	26	19	21	11	3	5	18	23	0	6	29	2	7	17	2
8	0	10	13	9	12	24	19	21	17	10	24	15	20	14	20	22	14	3	21	0	6	16	21	9
7	25	0	21	20	24	24	25	9	0	27	26	3	4	24	10	29	20	16	2	22	23	10	29	29
15	15	29	0	27	19	17	14	6	9	26	14	3	15	7	26	29	14	22	5	23	18	1	10	0
7	25	16	23	0	11	27	22	26	8	22	21	20	20	28	21	21	14	7	4	27	15	18	21	18
27	21	7	3	29	0	15	0	20	23	22	14	13	17	1	0	20	27	28	16	3	17	18	3	28
8	25	3	18	0	11	0	26	27	20	19	7	28	3	23	0	14	5	23	22	10	7	22	10	15
0	0	26	12	25	0	27	0	14	11	18	26	29	0	25	15	22	4	1	26	22	8	25	0	8
3	29	26	29	20	25	12	23	0	24	5	10	23	25	10	25	15	15	4	18	23	3	4	20	11
16	24	3	10	27	29	25	19	29	0	20	27	27	15	7	13	6	5	12	2	15	3	13	3	27
5	7	6	17	26	29	14	8	2	1	0	15	0	6	4	11	0	0	4	6	19	27	4	29	22
15	13	22	16	12	3	7	27	23	0	7	0	26	16	19	18	11	7	26	10	13	28	24	0	17
18	0	4	4	20	9	15	18	21	11	19	11	0	22	17	2	24	5	1	13	5	28	6	12	17
18	22	7	24	13	5	29	27	26	2	7	15	23	0	20	28	16	21	27	27	7	18	0	19	0
10	16	21	3	19	23	28	20	24	23	9	8	21	12	0	11	24	4	13	25	29	15	17	8	11
8	3	29	15	9	29	8	4	3	21	21	6	24	27	12	0	25	1	12	2	2	13	21	14	14
7	22	14	13	11	3	15	26	9	26	26	29	23	18	27	24	0	7	16	18	15	14	4	9	20
23	3	14	7	2	17	6	9	22	18	24	13	18	12	14	27	28	0	16	11	0	12	18	8	28

28	5	19	19	3	16	29	16	6	20	22	0	4	25	21	11	29	6	0	10	16	3	3	5	18
1	25	19	27	27	6	7	27	22	24	26	27	9	10	11	26	12	23	20	0	20	6	2	6	14
15	27	7	5	8	23	10	12	4	14	11	22	25	0	1	19	17	21	0	1	0	5	20	26	12
28	8	6	18	26	28	14	23	13	2	11	3	28	27	1	9	22	22	12	20	23	0	18	29	22
2	28	6	22	17	3	2	4	16	0	25	15	28	24	16	5	15	24	24	13	8	14	0	21	9
7	4	6	14	11	17	8	15	19	9	5	18	17	10	8	6	27	5	4	28	22	26	29	0	12
26	21	7	11	2	4	1	2	17	13	25	28	15	18	10	27	19	8	1	17	26	18	24	10	0

Traffic Matrix for 30 Node Network

- High Traffic

0	13	63	22	9	20	68	72	56	56	39	31	31	43	65	28	73	10	6	9	12	37	7	52	68	20	63	69
0	9	71	27	30	64	75	40	24	30	22	4	3	21	70	36	36	31	9	77	35	11	30	64	54	25	29	30
63	0	54	24	40	69	20	16	52	52	13	10	29	79	45	15	49	7	79	57	24	36	9	76	24	53	5	47
34	32	0	65	63	18	1	10	50	57	35	16	43	11	67	42	66	8	52	41	30	0	18	11	51	14	47	4
38	51	18	0	7	71	67	73	19	35	70	70	33	42	14	33	27	41	30	20	37	78	6	23	37	8	13	68
13	68	0	11	0	26	67	30	9	47	28	63	33	60	74	65	23	72	50	27	22	50	65	30	40	76	62	25
4	51	38	26	19	0	0	55	55	2	34	21	46	2	68	5	70	38	3	9	66	79	10	55	12	73	54	75
15	10	15	5	65	14	0	68	33	33	74	40	21	36	44	23	40	57	39	55	29	9	10	47	17	55	27	13
32	52	75	33	13	63	37	0	15	17	56	37	56	39	14	8	42	1	15	70	76	14	21	10	40	44	26	79
79	22	5	53	52	76	32	3	0	57	67	63	30	67	36	26	39	8	71	27	16	40	33	48	74	30	37	8
54	10	39	5	58	51	21	69	31	0	62	17	12	4	55	71	33	65	18	16	22	37	48	52	77	4	23	75
16	62	7	45	43	20	38	16	11	47	0	7	37	18	10	49	10	40	76	41	53	9	73	18	10	34	63	49
52	1	34	54	13	45	29	45	57	58	41	0	8	23	69	55	29	9	68	74	3	61	31	36	44	37	32	5
62	52	3	1	4	4	77	42	4	3	31	33	0	15	66	79	66	56	59	3	38	57	4	67	36	28	5	14
70	3	43	64	7	42	47	76	49	32	68	24	13	0	38	42	14	7	48	26	71	40	32	78	38	38	28	55
3	36	19	76	26	0	72	30	54	35	11	71	19	76	0	20	56	23	73	15	48	1	65	29	77	57	6	17
34	26	37	49	60	1	26	52	13	20	10	56	12	6	34	0	65	7	27	75	58	63	70	62	14	44	31	72
31	19	77	41	40	31	15	40	6	72	68	58	66	18	26	28	0	14	23	23	42	31	13	48	37	31	39	72
60	63	38	49	12	42	48	56	32	77	63	42	64	16	70	75	65	0	8	44	66	5	55	44	4	73	58	24
17	64	66	4	51	77	38	65	19	19	15	48	57	20	38	46	77	15	0	34	68	2	36	39	62	16	61	7
74	41	62	57	73	45	78	35	58	0	37	79	8	51	47	56	28	64	10	0	79	27	18	51	6	66	78	10
22	36	8	31	48	16	47	32	68	77	37	58	14	30	13	39	49	24	71	54	0	21	76	8	25	13	27	3
19	23	43	4	55	36	8	14	51	62	53	49	65	45	37	16	75	9	0	33	8	0	22	79	62	20	66	26
2	38	5	36	37	59	65	71	17	72	32	58	11	45	24	26	75	42	24	10	57	67	0	15	52	58	57	7
7	57	53	73	48	23	65	55	9	9	33	75	57	49	30	48	38	38	3	24	31	60	62	0	73	65	62	29
50	64	69	22	40	57	20	17	45	3	18	30	23	74	0	19	36	6	0	15	16	68	37	8	0	46	5	42
76	5	64	3	25	55	49	59	3	39	22	27	19	76	43	78	55	57	33	8	29	14	45	0	26	0	54	0
2	15	31	14	64	63	46	43	75	43	17	31	58	1	72	11	46	23	39	34	30	42	2	25	2	36	0	33
78	71	49	53	77	57	53	70	43	69	47	51	69	55	45	69	68	29	52	51	50	50	45	31	50	14	44	0
33	16	14	23	76	47	8	14	16	23	10	9	55	42	66	9	63	9	53	4	19	64	2	73	3	31	19	67

- Medium Traffic

0	33	43	12	29	0	8	2	6	6	19	11	1	43	5	8	43	30	16	19	32	17	47	22	18	30	23	49
0	19	1	27	40	24	35	20	44	10	12	34	13	1	10	36	26	31	29	47	25	41	40	44	34	25	29	30
43	0	34	4	10	49	20	6	32	22	13	40	9	19	5	45	49	27	19	47	24	46	49	6	34	43	45	7
4	2	0	15	33	38	1	40	30	37	45	6	13	11	27	42	6	18	12	1	10	30	8	21	31	14	47	14
38	31	18	0	37	1	37	13	29	45	0	0	13	12	34	23	47	21	30	40	7	28	26	3	47	8	43	38
43	38	20	11	0	46	37	10	9	37	18	3	23	0	24	5	33	2	20	37	2	10	5	10	0	46	42	35
24	31	8	36	19	0	0	15	5	32	24	11	6	2	18	15	20	18	23	39	6	19	30	5	32	43	24	45
5	30	45	45	5	44	0	48	23	3	24	10	41	6	44	43	40	37	29	35	49	29	10	7	17	5	37	23
12	22	45	3	3	33	17	0	5	17	26	27	26	49	4	28	2	11	5	20	16	44	31	30	30	4	36	9
29	2	15	3	32	36	32	13	0	17	7	33	10	17	16	46	19	28	21	7	6	20	3	28	4	30	27	48
14	10	19	25	48	31	1	9	1	0	22	17	2	24	45	21	3	25	28	16	42	47	38	32	17	4	43	45
36	2	17	45	13	40	48	46	1	7	0	17	47	28	0	9	30	10	16	11	43	9	3	48	30	34	43	39
42	1	24	44	43	15	49	15	37	8	41	0	48	43	29	15	39	9	38	4	43	1	21	16	14	27	12	5
32	42	23	1	24	4	37	2	4	13	41	23	0	25	6	9	26	46	9	13	8	27	34	47	6	48	5	4
30	23	33	24	47	2	47	26	49	42	38	4	33	0	8	42	14	17	28	6	41	0	42	18	48	18	18	25
13	46	29	16	16	40	32	30	14	5	21	11	29	46	0	0	16	3	43	5	28	31	5	29	37	47	36	7
4	6	7	29	30	41	16	2	33	10	40	16	32	6	14	0	35	47	27	35	8	33	10	42	24	4	21	22
21	29	17	31	30	41	25	0	46	32	18	8	26	28	16	18	0	4	3	13	22	11	43	48	7	31	19	12
20	23	38	9	2	22	28	26	2	17	23	2	4	36	0	35	25	0	28	14	26	15	25	4	14	23	8	24
27	24	26	4	1	37	38	25	29	19	25	38	47	20	28	16	47	5	0	24	28	2	26	29	32	26	11	27
24	11	42	47	33	5	18	25	38	20	7	39	38	21	27	6	18	14	20	0	29	17	38	11	6	46	28	20
42	46	8	21	18	26	7	12	48	17	7	18	4	40	3	39	49	34	11	24	0	21	36	28	35	43	17	43
39	33	33	34	15	46	38	34	1	22	13	39	25	35	47	26	15	49	40	13	38	0	22	29	32	40	16	46
22	28	45	36	7	49	35	21	17	42	32	48	31	45	34	36	35	2	4	0	27	37	0	45	42	28	37	37
37	7	3	3	38	33	35	25	39	9	3	45	47	19	20	18	38	48	33	44	41	0	42	0	3	35	2	39
40	44	19	42	10	47	0	27	25	33	28	0	3	44	30	9	6	26	20	25	46	48	17	8	0	26	45	32
36	45	4	43	25	5	19	9	23	29	32	7	39	6	23	18	35	47	3	8	19	34	35	20	6	0	14	30
12	25	21	14	44	13	26	43	25	23	7	11	18	11	22	11	16	23	39	24	10	2	22	45	22	36	0	33
28	11	9	13	37	17	13	0	3	19	37	41	49	5	5	29	18	29	2	11	0	20	45	41	40	24	14	0
3	16	24	33	16	7	8	44	6	13	40	49	45	32	6	49	23	49	3	14	39	14	2	23	43	11	9	47

- Low Traffic

0	0	23	3	2	29	0	18	22	6	26	19	21	11	3	5	18	23	0	6	29	2	7	17	2	8	10	13	9	12
24	0	19	21	17	10	24	15	20	14	20	22	14	3	21	0	6	16	21	9	7	25	21	20	24	24	25	9	0	27
26	3	0	4	24	10	29	20	16	2	22	23	10	29	29	15	15	29	27	19	17	14	6	9	26	14	3	15	7	26
29	14	22	0	5	23	18	1	10	0	7	25	16	23	11	27	22	26	8	22	21	20	20	28	21	21	14	7	4	27
15	18	21	18	0	27	21	7	3	29	15	0	20	23	22	14	13	17	1	0	20	27	28	16	3	17	18	3	28	8
25	3	18	0	11	0	26	27	20	19	7	28	3	23	0	14	5	23	22	10	7	22	10	15	0	0	26	12	25	0
27	14	11	18	26	29	0	0	25	15	22	4	1	26	22	8	25	0	8	3	29	26	29	20	25	12	23	24	5	10
23	25	10	25	15	15	4	0	18	23	3	4	20	11	16	24	3	10	27	29	25	19	29	20	27	27	15	7	13	6
5	12	2	15	3	13	3	27	0	5	7	6	17	26	29	14	8	2	1	15	0	6	4	11	0	0	4	6	19	27
4	29	22	15	13	22	16	12	3	0	7	27	23	0	7	26	16	19	18	11	7	26	10	13	28	24	0	17	18	0
4	4	20	9	15	18	21	11	19	11	0	22	17	2	24	5	1	13	5	28	6	12	17	18	22	7	24	13	5	29
27	26	2	7	15	23	20	28	16	21	27	0	27	7	18	0	19	0	10	16	21	3	19	23	28	20	24	23	9	8
21	12	11	24	4	13	25	29	15	17	8	11	0	8	3	29	15	9	29	8	4	3	21	21	6	24	27	12	25	1
12	2	2	13	21	14	14	7	22	14	13	11	3	0	15	26	9	26	26	29	23	18	27	24	7	16	18	15	14	4
9	20	23	3	14	7	2	17	6	9	22	18	24	13	0	18	12	14	27	28	16	11	0	12	18	8	28	28	5	19
19	3	16	29	16	6	20	22	0	4	25	21	11	29	6	0	10	16	3	3	5	18	1	25	19	27	27	6	7	27
22	24	26	27	9	10	11	26	12	23	20	20	6	2	6	14	0	15	27	7	5	8	23	10	12	4	14	11	22	25
0	1	19	17	21	0	1	5	20	26	12	28	8	6	18	26	28	0	14	23	13	2	11	3	28	27	1	9	22	22
12	20	23	18	29	22	2	28	6	22	17	3	2	4	16	0	25	15	0	28	24	16	5	15	24	24	13	8	14	21
9	7	4	6	14	11	17	8	15	19	9	5	18	17	10	8	6	27	5	0	4	28	22	26	29	12	26	21	7	11
2	4	1	2	17	13	25	28	15	18	10	27	19	8	1	17	26	18	24	10	0	29	17	28	1	26	16	8	0	20
24	22	6	28	21	28	16	27	12	28	7	17	28	24	20	13	19	19	14	11	24	0	1	16	28	25	3	27	13	1
24	9	23	23	14	25	6	28	14	21	22	13	29	15	25	27	16	15	9	10	3	18	0	22	29	22	10	6	26	0
23	22	28	15	6	17	29	25	11	17	22	12	28	21	15	14	6	15	22	24	10	7	17	0	15	12	28	27	17	19
25	17	7	23	13	8	3	25	15	19	9	13	5	7	29	0	18	8	28	3	24	1	0	2	0	3	5	2	9	5
19	20	4	19	22	20	27	0	27	25	13	8	20	13	14	10	9	6	6	0	15	16	8	17	18	0	26	15	22	14
16	16	25	24	13	5	15	29	19	3	9	12	27	29	16	3	18	5	27	23	8	9	14	15	0	26	0	4	10	10
19	2	5	21	14	24	13	6	23	5	23	27	1	8	1	22	21	26	13	9	4	20	2	12	5	22	26	0	13	17
24	18	11	29	13	27	17	13	20	13	19	7	1	29	5	15	9	28	9	2	11	0	10	25	21	0	4	4	0	27
8	13	6	14	3	16	7	28	24	16	23	10	29	15	22	6	19	3	9	3	14	29	24	2	13	3	11	29	7	0

Appendix C: Commodity Table

Commodity table is a data structure which is used to store the information of the chains. Commodity table is a two dimensional array of structure commodity list. That means in each cell of commodity table, we have an object of type commodity structure.

Commodity list structure comprises of four fields. First field is number of chains. A chain defines a specific traffic request in the traffic matrix. For example, we have an entry in the traffic matrix as from node 0 to node 3 the amount of traffic is 30. Now, the chain contains all the lightpaths that are required to serve that traffic request.

Second field is traffic on that chain. Third field is a pointer to the number of lightpaths in that chain. Fourth field is a double pointer in which each pointer points to an array of lightpaths comprised the chain.

Appendix D: Test Results For Different N-node Networks

1. Performance Testing With 6-Node Networks

6 Node Network		Our Approach		Shared Protection		Dedicated Protection	
Traffic Matrix	Wavelength Channels	Avg. # of lightpaths	Avg. Channel Used	Avg. # of lightpaths	Avg. Channel Used	Avg. # of lightpaths	Avg. Channel Used
T11 to T15 (High)	8	29	49	35	49	35	99
	16	29	49	35	49	35	99
	32	29	49	35	49	35	99
T6 to T10 (Medium)	8	25	41	31	45	31	56
	16	25	41	31	45	31	56
	32	25	41	31	45	31	56
T1 to T5 (Low)	8	20	34	25	36	25	45
	16	20	34	25	36	25	45
	32	20	34	25	36	25	45

6 Node Network		Our Approach	Shared Protection	Dedicated Protection
Traffic Matrix	Wavelength Channels	Failure	Failure	Failure
T11 to T15 (High)	8	0	0	0
	16	0	0	0
	32	0	0	0
T6 to T10 (Medium)	8	0	0	0
	16	0	0	0
	32	0	0	0
T1 to T5 (Low)	8	0	0	0
	16	0	0	0
	32	0	0	0

2. Performance Testing With 8-Node Networks

8 Node Network		Our Approach		Shared Protection		Dedicated Protection	
Traffic Matrix	Wavelength Channels	Avg. # of lightpaths	Avg. Channel Used	Avg. # of lightpaths	Avg. Channel Used	Avg. # of lightpaths	Avg. Channel Used
T11 to T15 (High)	8	53	105	66	105	66	207
	16	53	108	66	110	66	213
	32	53	108	66	110	66	213
T6 to T10 (Medium)	8	41	79	54	90	54	119
	16	41	79	54	91	54	119
	32	41	79	54	91	54	119
T1 to T5 (Low)	8	33	64	42	73	42	93
	16	33	64	42	73	42	94
	32	33	64	42	73	42	94

8 Node Network		Our Approach	Shared Protection	Dedicated Protection
Traffic Matrix	Wavelength Channels	Failure	Failure	Failure
T11 to T15 (High)	8	2	6	23
	16	0	0	0
	32	0	0	0
T6 to T10 (Medium)	8	0	0	2
	16	0	0	0
	32	0	0	0
T1 to T5 (Low)	8	0	0	0
	16	0	0	0
	32	0	0	0

3. Performance Testing For 10-Node Networks

10 Node Network		Our Approach		Shared Protection		Dedicated Protection	
Traffic Matrix	Wavelength Channels	Avg. # of lightpaths	Avg. Channel Used	Avg. # of lightpaths	Avg. Channel Used	Avg. # of lightpaths	Avg. Channel Used
T11 to T15 (High)	8	79	158	104	158	103	295
	16	79	162	104	169	104	334
	32	79	162	104	169	104	334
T6 to T10 (Medium)	8	62	121	85	142	85	169
	16	62	121	86	142	86	190
	32	62	121	86	142	86	190
T1 to T5 (Low)	8	50	96	70	117	69	151
	16	50	96	70	117	70	154
	32	50	96	70	117	70	154

10 Node Network		Our Approach	Shared Protection	Dedicated Protection
Traffic Matrix	Wavelength Channels	Failure	Failure	Failure
T11 to T15 (High)	8	0	16	32
	16	0	0	0
	32	0	0	0
T6 to T10 (Medium)	8	0	0	24
	16	0	0	0
	32	0	0	0
T1 to T5 (Low)	8	0	0	6
	16	0	0	0
	32	0	0	0

4. Performance Testing For 14-Node Networks

14 Node Network	Wavelength Channels	Our Approach		Shared Protection		Dedicated Protection	
Traffic Matrix		Avg. # of lightpaths	Avg. Channel Used	Avg. # of lightpaths	Avg. Channel Used	Avg. # of lightpaths	Avg. Channel Used
T11 to T15 (High)	8	0	0	0	0	0	0
	16	166	435	219	455	0	0
	32	166	445	220	474	220	883
T6 to T10 (Medium)	8	118	263	0	0	0	0
	16	120	306	168	364	169	485
	32	120	306	168	368	168	508
T1 to T5 (Low)	8	95	226	0	0	0	0
	16	96	239	141	313	140	419
	32	96	239	141	314	141	427

14 Node Network	Wavelength Channels	Our Approach	Shared Protection	Dedicated Protection
Traffic Matrix		Failure	Failure	Failure
T11 to T15 (High)	8	50	50	50
	16	3	12	50
	32	0	0	0
T6 to T10 (Medium)	8	30	50	50
	16	0	1	28
	32	0	0	0
T1 to T5 (Low)	8	4	50	50
	16	0	0	3
	32	0	0	0

5. Performance Testing For 20-Node Networks

20 Node Network		Our Approach		Shared Protection		Dedicated Protection	
Traffic Matrix	Wavelength Channels	Avg. # of lightpaths	Avg. Channel Used	Avg. # of lightpaths	Avg. Channel Used	Avg. # of lightpaths	Avg. Channel Used
T11 to T15 (High)	8	0	0	0	0	0	0
	16	323	777	461	839	0	0
	32	323	784	460	851	460	1689
T6 to T10 (Medium)	8	244	520	0	0	0	0
	16	247	583	364	688	370	955
	32	247	583	362	686	362	967
T1 to T5 (Low)	8	185	417	291	509	0	0
	16	186	428	293	566	292	781
	32	186	428	293	565	293	781

20 Node Network		Our Approach	Shared Protection	Dedicated Protection
Traffic Matrix	Wavelength Channels	Failure	Failure	Failure
T11 to T15 (High)	8	50	50	50
	16	0	6	50
	32	0	0	0
T6 to T10 (Medium)	8	32	50	50
	16	0	0	32
	32	0	0	0
T1 to T5 (Low)	8	0	48	50
	16	0	0	0
	32	0	0	0

6. Performance Testing For 25-Node Networks

25 Node Network		Our Approach		Shared Protection		Dedicated Protection	
Traffic Matrix	Wavelength Channels	Avg. # of lightpaths	Avg. Channel Used	Avg. # of lightpaths	Avg. Channel Used	Avg. # of lightpaths	Avg. Channel Used
T11 to T15 (High)	8	0	0	0	0	0	0
	16	502	1222	731	1303	0	0
	32	505	1301	735	1394	734	2816
T6 to T10 (Medium)	8	0	0	0	0	0	0
	16	390	968	601	1134	0	0
	32	390	968	601	1160	601	1702
T1 to T5 (Low)	8	284	644	0	0	0	0
	16	287	698	460	907	421	1242
	32	287	698	461	907	461	1303

25 Node Network		Our Approach	Shared Protection	Dedicated Protection
Traffic Matrix	Wavelength Channels	Failure	Failure	Failure
T11 to T15 (High)	8	50	50	50
	16	3	48	50
	32	0	0	1
T6 to T10 (Medium)	8	50	50	50
	16	0	8	50
	32	0	0	0
T1 to T5 (Low)	8	17	50	50
	16	0	0	46
	32	0	0	0

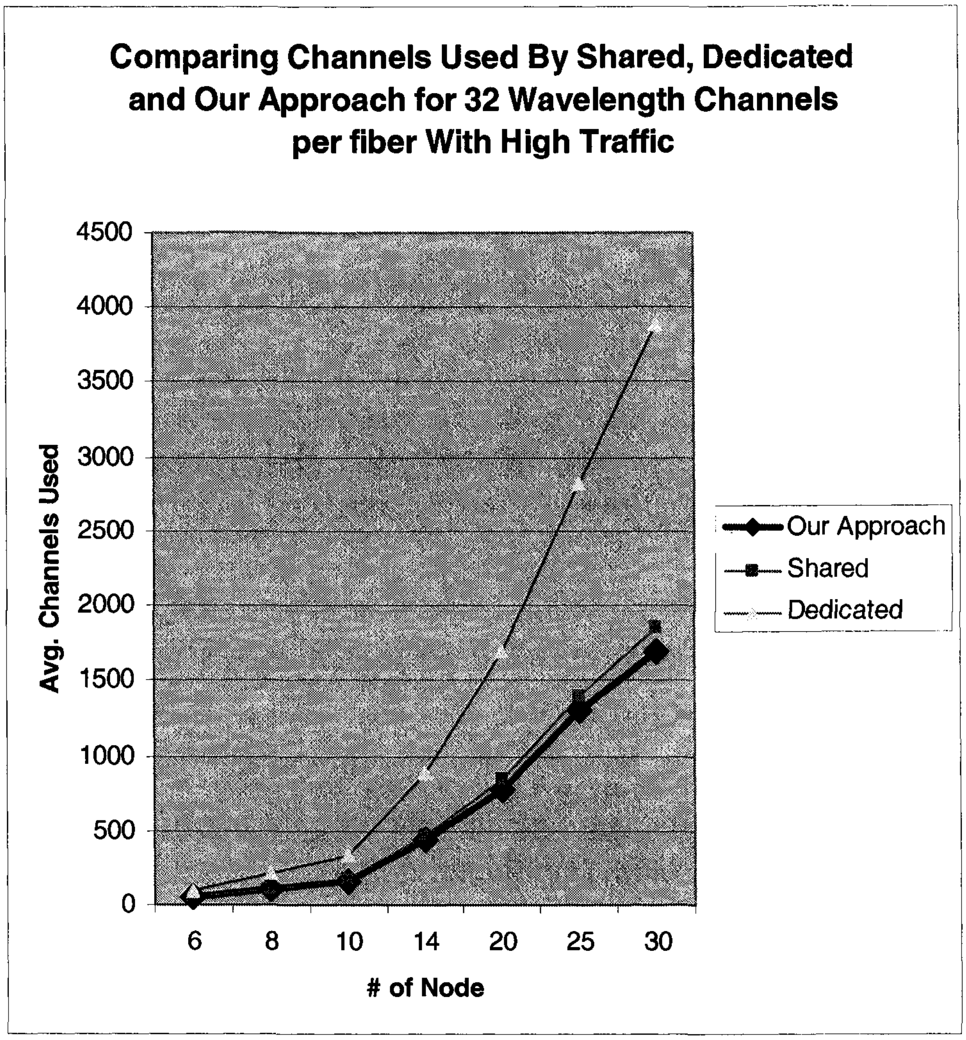
7. Performance Testing For 30-Node Networks

30 Node Network	Wavelength Channels	Our Approach		Shared Protection		Dedicated Protection	
Traffic Matrix		Avg. # of lightpaths	Avg. Channel Used	Avg. # of lightpaths	Avg. Channel Used	Avg. # of lightpaths	Avg. Channel Used
T11 to T15 (High)	8						
	16						
	32	719	1698	1083	1849	1083	3876
T6 to T10 (Medium)	8						
	16						
	32	552	1267	883	1534	883	2276
T1 to T5 (Low)	8						
	16						
	32	411	926	682	1209	682	1753

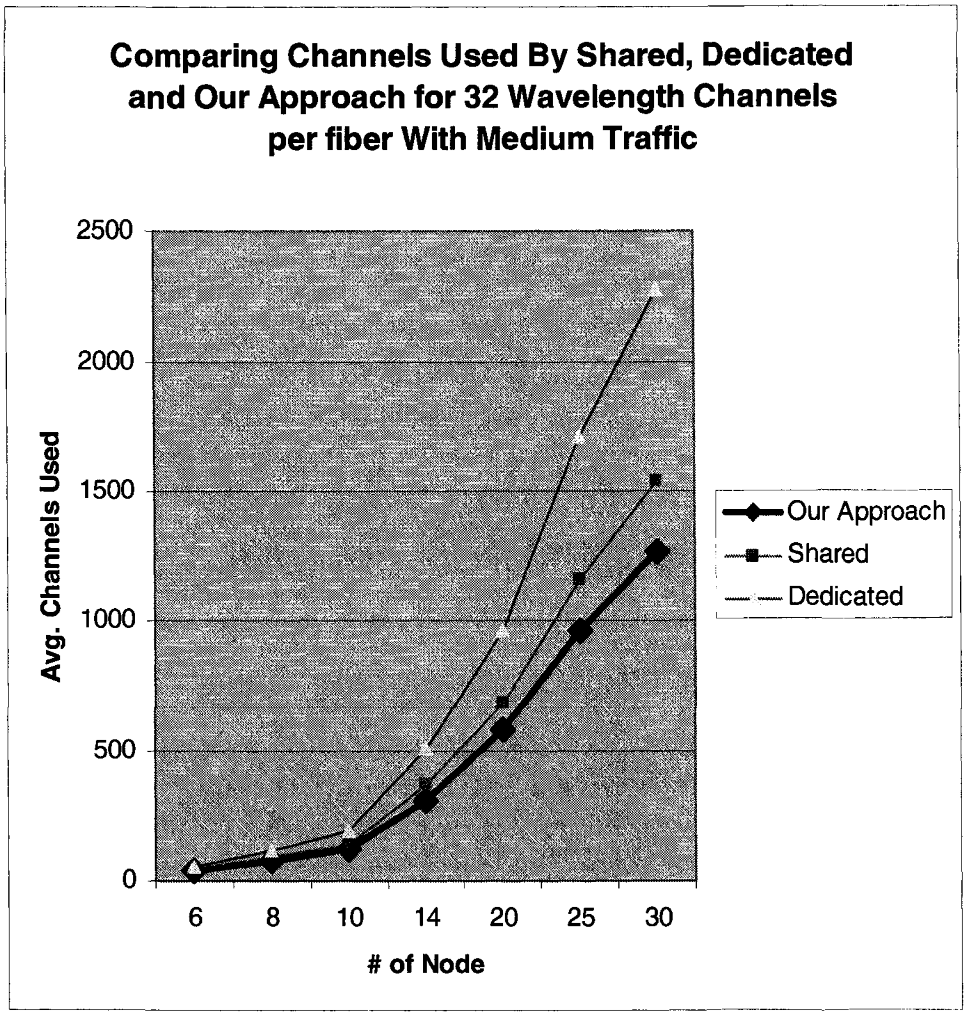
30 Node Network	Wavelength Channels	Our Approach	Shared Protection	Dedicated Protection
Traffic Matrix		Failure	Failure	Failure
T11 to T15 (High)	8			
	16			
	32	0	0	0
T6 to T10 (Medium)	8			
	16			
	32	0	0	0
T1 to T5 (Low)	8			
	16			
	32	0	0	0

Appendix E: Channels Used as Graphs

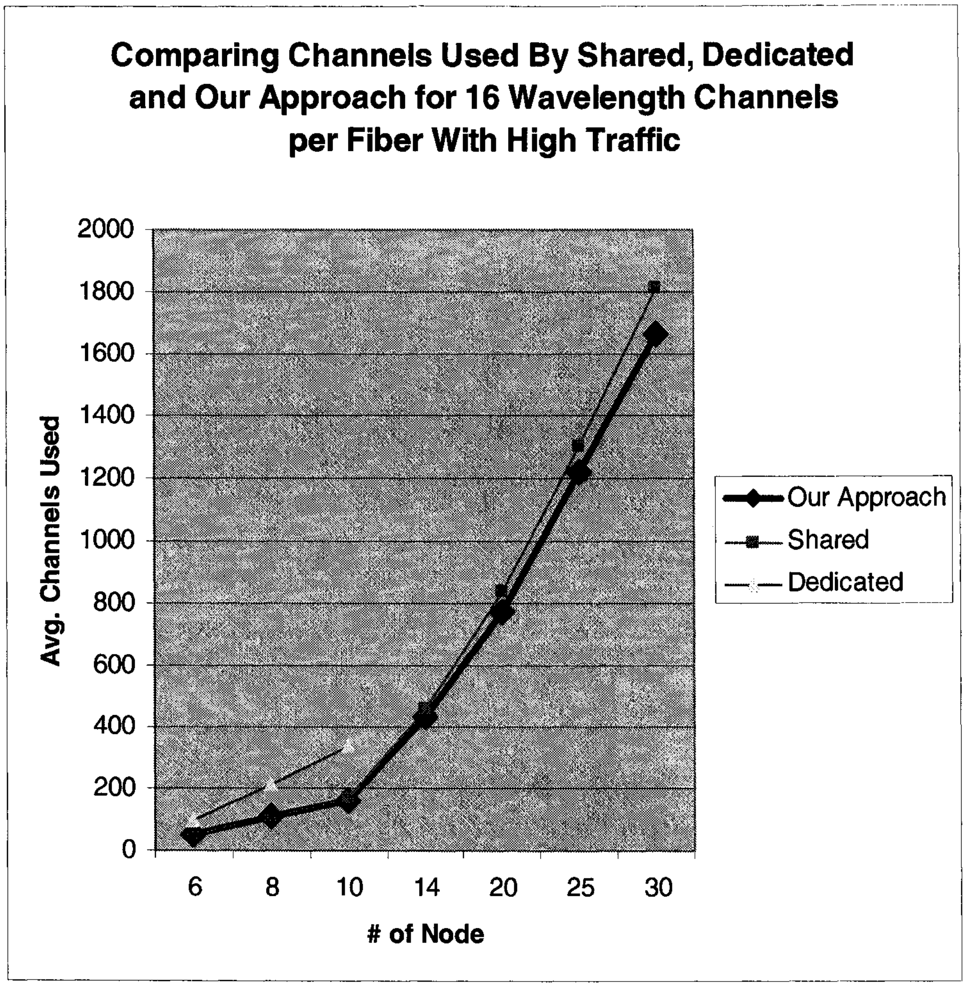
➢ **Graph for 32 wavelength Channels and High traffic load.**



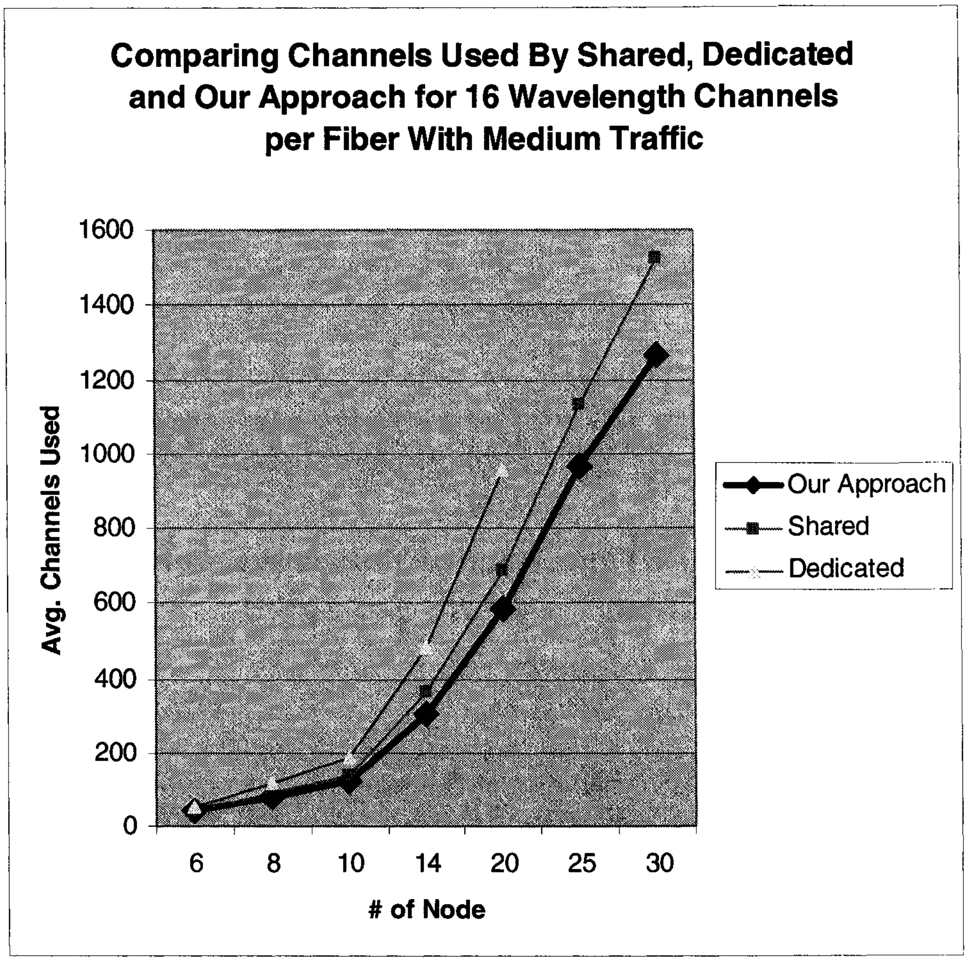
➢ **Graph for 32 wavelength Channels and Medium traffic load.**



➢ **Graph for 16 wavelength Channels and High traffic load.**



➢ **Graph for 16 wavelength Channels and Medium traffic load.**



Appendix F: 95% Confidence Interval for Channels Used

➢ **95% C.I. for channels used under high traffic condition.**

High		H1vSP		H1vDP		SPvDP	
		95% Confidence Interval		95% Confidence Interval		95% Confidence Interval	
Node Number	Wave length Channels	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound
6	8	1.41	2.47	21.36	24.24	21.55	23.10
	16	1.41	2.47	21.36	24.24	21.55	23.10
	32	1.41	2.47	21.36	24.24	21.55	23.10
8	8	0.70	2.98	23.58	26.86	21.99	26.15
	16	0.69	3.08	24.99	27.53	23.83	26.53
	32	0.69	3.08	24.99	27.53	23.83	26.53
10	8	3.52	6.24	17.75	23.32	13.68	19.20
	16	2.78	5.95	28.45	30.66	25.81	26.80
	32	2.78	5.95	28.43	30.64	25.79	26.77
14	8	-	-	-	-	-1.50	0.98
	16	3.98	5.95	15.87	18.62	11.30	14.38
	32	4.66	6.93	31.82	33.64	27.64	29.44
20	8	-	-	-	-	-	-
	16	7.32	8.66	25.81	27.52	19.38	21.16
	32	7.09	8.65	35.67	36.67	30.28	31.10
25	8	-	-	-	-	-	-
	16	6.66	7.51	9.56	11.09	2.84	4.14
	32	6.17	7.19	37.14	37.90	32.75	33.33
30	8	-	-	-	-	-	-
	16	8.66	9.47	18.50	20.08	10.41	12.05
	32	7.69	8.57	38.88	39.50	33.53	34.06

➤ **95% C.I. for channels used under medium traffic condition.**

High		Our vs. Shared Protection		Dedicated vs. Our Approach		Dedicated vs. Shared Protection	
Node Number	Wave length Channels	95% Confidence Interval		95% Confidence Interval		95% Confidence Interval	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound
6	8	6.90	10.55	25.17	28.22	18.72	20.57
	16	6.90	10.55	25.17	28.22	18.72	20.57
	32	6.90	10.55	25.17	28.22	18.72	20.57
8	8	9.80	14.52	31.49	35.15	22.50	25.35
	16	10.07	14.72	31.66	35.13	22.84	24.89
	32	10.07	14.72	31.66	35.13	22.84	24.89
10	8	13.53	16.97	30.90	34.36	19.18	21.81
	16	13.50	16.84	35.11	37.53	24.27	25.49
	32	13.50	16.84	35.11	37.53	24.27	25.49
14	8	-	0.92	-	1.02	-	1.02
	16	14.85	17.04	36.02	37.66	23.50	25.96
	32	15.26	17.88	38.73	40.60	26.56	28.60
20	8	-	0.83	-	1.31	-	1.03
	16	14.44	15.87	39.32	40.51	28.35	29.92
	32	14.36	15.59	39.32	40.18	28.68	29.56
25	8	-	-	-	-	-	-
	16	14.60	15.81	26.79	28.90	13.77	16.02
	32	15.88	17.08	42.68	43.47	31.49	32.15
30	8	-	-	-	-	-	-
	16	16.38	17.23	37.32	38.75	24.85	26.21
	32	17.03	17.78	44.10	44.57	32.31	32.88

Appendix G: 95% Confidence Interval for Lightpaths Used

➢ **95% C.I. for lightpaths used under high traffic condition.**

High	Wave length Channels	Our vs. Shared Protection		Dedicated vs. Our Approach	
Node Number		95% Confidence Interval		95% Confidence Interval	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
6	8	13.91	19.49	13.91	19.49
	16	13.91	19.49	13.91	19.49
	32	13.91	19.49	13.91	19.49
8	8	18.63	21.42	18.63	21.39
	16	18.63	21.42	18.62	21.42
	32	18.63	21.42	18.62	21.42
10	8	26.11	28.30	25.36	27.91
	16	26.11	28.30	26.10	28.29
	32	26.11	28.30	26.10	28.29
14	8	23.95	26.08	-	-
	16	30.87	32.08	30.51	31.93
	32	31.00	32.18	31.06	32.23
20	8	33.93	35.12	10.83	12.81
	16	35.91	36.78	35.69	36.50
	32	35.91	36.78	35.91	36.78
25	8	20.13	22.22	-	-
	16	37.46	37.91	37.46	38.18
	32	37.53	37.96	37.53	37.95
30	8	31.48	33.18	1.32	3.46
	16	39.43	39.92	39.61	40.14
	32	39.43	39.92	39.43	39.92

➢ **95% C.I. for lightpaths used under low traffic condition.**

High	Wave length Channels	Our vs. Shared Protection		Dedicated vs. Our Approach	
Node Number		95% Confidence Interval		95% Confidence Interval	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
6	8	15.60	17.43	15.60	17.43
	16	15.60	17.43	15.60	17.43
	32	15.60	17.43	15.60	17.43
8	8	19.39	21.03	16.61	19.35
	16	18.67	20.44	18.67	20.44
	32	18.67	20.44	18.67	20.44
10	8	22.33	24.33	9.54	17.25
	16	22.39	24.41	22.39	24.41
	32	22.39	24.41	22.39	24.41
14	8	-	-	-	-
	16	23.54	24.79	9.54	13.09
	32	23.99	24.94	23.97	25.01
20	8	-	-	-	-
	16	29.85	30.48	22.82	24.51
	32	29.39	30.11	29.39	30.11
25	8	-	-	-	-
	16	31.82	32.82	2.33	4.83
	32	30.98	31.50	30.80	31.40
30	8	-	-	-	-
	16	34.70	35.31	14.60	16.31
	32	33.31	33.77	33.27	33.77

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